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Dynamics of forest landscapes in Amazonian territories in transition: analysis of ecological processes and production of indicators

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ABSTRACT

Title: Dynamics of forest landscapes in Amazonian territories in transition: analysis of ecological processes and production of indicators

Keywords: Amazonia, deforestation, forest degradation, regrowth, archetypes, indicators

Abstract: Forest cover change in the Amazon is the result of complex interactions between ecological processes, institutional dynamics, and land-use decisions, leading to heterogeneous forest landscapes with varying degrees of degradation, deforestation, and regeneration. This PhD thesis aims to contribute to the understanding of forest landscape transformations at the subnational territorial scale by addressing two interrelated objectives: (i) Identifying indicators related to forest cover change will help forest cover management at a territorial scale; (ii) Evaluating how forest cover processes in the Amazon create diverse forest landscapes and the consequences. The study is guided by three central research questions: (1) How can landscape units reflecting the transformation processes of deforestation, degradation and regeneration be stratified? (2) What is the relationship between transformation processes and changes in landscape structure (composition and configuration), fire dynamics and legal territorial designations? An operational research question is also addressed: How can landscape change analysis help us identify indicators of forest cover change that are useful for decision making?. A typology of landscape trajectories was developed based on forest cover dynamics from 1990 to 2021, enabling the classification of territorial archetypes. These archetypes reflect the spatial interplay of degradation, deforestation, and regeneration and serve as a basis for assessing management priorities and informing policy interventions. Additionally, the analysis incorporated landscape structure, fire dynamics, and legal designations within archetypes by integrating multiple open-source datasets (TMF-JRC, MapBiomas, MODIS-Fire, and GLAD-Fire). Complementing the spatial analysis, participatory workshops and semi-structured interviews were conducted in Cotriguaçu (Brazil) to assess forest governance capacities. The findings show that forest cover change processes are not isolated but rather interconnected dynamics that collectively shape landscape complexity. Four distinct archetypes were identified: rampant frontiers, past gradual frontiers, consolidated frontiers, and vulnerable frontiers. Their spatial distribution highlights priority areas for restoration, fire management, and tailored governance strategies. In Paragominas, significant forest regeneration was observed, driven by pasture abandonment and transitions from pasture to regrowth, closely linked to the “Green Municipality” initiative. In contrast, Guaviare exhibited active deforestation associated with the expansion of agricultural frontiers. Cotriguaçu displayed a complex mosaic of forest degradation and intermittent fire use, shaped mainly by its colonization history. While statistical tests did not reveal significant differences among stakeholder groups regarding forest governance themes, discourse analysis uncovered critical divergences in values, capacities, and interpretations of sustainability. In Cotriguaçu, participatory mapping revealed partial convergence around restoration goals but also exposed governance asymmetries between institutional actors and local producers. This thesis highlights the importance of integrating multiscale data,

archetypes-based analysis, and local stakeholder perspectives to develop governance mechanisms that are more context-sensitive, inclusive, and adaptive. It contributes to advancing emerging frameworks for territorial sustainability in tropical forest landscapes facing growing socio-environmental pressures towards a more sustainable transition.

RÉSUMÉ

Titre: Evolution des paysages forestiers dans des territoires amazoniens en transition: analyse des processus écologiques et production d'indicateurs de durabilité

Mots-clés: Amazonie, déforestation, dégradation forestière, régénération, archétypes, indicateurs

Résumé: Le changement de la couverture forestière en Amazonie résulte d'interactions complexes entre les processus écologiques, la dynamique institutionnelle et les décisions en matière d'utilisation des terres, conduisant à des paysages forestiers hétérogènes présentant des degrés variables de dégradation, de déforestation et de régénération. Cette thèse vise à contribuer à la compréhension des transformations du paysage forestier à l'échelle territoriale infranationale en abordant deux objectifs: (i) l'identification d'indicateurs liés au changement de la couverture forestière afin de faciliter la gestion de la couverture forestière à l'échelle territoriale; (ii) l'évaluation de la manière dont les processus de couverture forestière en Amazonie créent des paysages forestiers diversifiés et de leurs conséquences. L'étude s'articule autour de trois questions de recherche centrales: (1) Comment stratifier les unités de paysage reflétant les processus de transformation de la déforestation, de la dégradation et de la régénération? (2) Quelle est la relation entre les processus de transformation et les changements dans la structure du paysage (composition et configuration), la dynamique des incendies et les désignations territoriales légales? Une question de recherche opérationnelle est également abordée: comment l'analyse des changements du paysage peut-elle nous aider à identifier des indicateurs de changement de la couverture forestière utiles à la prise de décision? Une typologie des trajectoires paysagères a été élaborée à partir de la dynamique du couvert forestier entre 1990 et 2021, permettant ainsi la classification des archétypes territoriaux. Ces archétypes reflètent l'interaction spatiale entre la dégradation, la déforestation et la régénération. En outre, l'analyse a intégré la structure du paysage, la dynamique des incendies et les désignations légales au sein des archétypes en combinant plusieurs ensembles de données open source (TMF-JRC, MapBiomass, MODIS-Fire et GLAD-Fire). En complément de l'analyse spatiale, des ateliers participatifs et des entretiens semi-structurés ont été organisés à Cotriguaçu (Brésil) afin d'évaluer les capacités de gouvernance forestière. Les résultats montrent que

les processus de changement de la couverture forestière ne sont pas isolés, mais constituent plutôt des dynamiques interconnectées. Quatre archétypes distincts ont été identifiés: les frontières rampantes, les anciennes frontières graduelles, les frontières consolidées et les frontières vulnérables. Leur répartition spatiale met en évidence les zones prioritaires pour la restauration, la gestion des incendies et les stratégies de gouvernance adaptées. À Paragominas, une régénération forestière importante a été observée, due à l'abandon des pâturages et à la transition de ceux-ci vers la repousse, étroitement liée à l'initiative « Municipalité verte ». En revanche, Guaviare a connu une déforestation active liée à l'expansion des frontières agricoles. Cotriguaçu a présenté une mosaïque complexe de dégradation forestière et d'utilisation intermittente du feu, principalement façonnée par son histoire coloniale. Si les tests statistiques n'ont pas révélé de différences significatives entre les groupes de parties prenantes en ce qui concerne les thèmes de la gouvernance forestière, l'analyse du discours a mis en évidence des divergences critiques en matière de valeurs, de capacités et d'interprétations de la durabilité. À Cotriguaçu, la cartographie participative a révélé une convergence partielle autour des objectifs de restauration. Cette thèse souligne l'importance d'intégrer des données à plusieurs échelles, afin de développer des mécanismes de gouvernance plus sensibles au contexte, plus inclusifs et plus adaptatifs. Elle contribue à faire progresser les cadres émergents pour la durabilité territoriale dans les paysages forestiers tropicaux confrontés à des pressions socio-environnementales croissantes vers une transition plus durable.

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List of abbreviations

ARI	Adjusted Rand Index
APPs	Permanent Preservation Areas
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CAR	Rural Environmental Registry
DETER	Real-Time Deforestation Detection System
ET	Evapotranspiration
ED	Edge Density
EC	European Commission
ENSO	El Niño-Southern Oscillation
FARC	Fuerzas Armadas Revolucionarias de Colombia
Glad-Fire	Global Forest Loss Due to Fire
ICV	Instituto Centro de Vida
IBGE	Brazilian National Institute of Geography and Statistics
IDEAM	Institute of Hydrology, Meteorology, and Environmental Studies
INPE	Brazilian National Institute for Space Research
Landsat	Data from the satellites have been used for monitoring land cover
LST	Land Surface Temperature
P	Precipitation
MODIS	Moderate Resolution Imaging Spectroradiometer
PRODES	Program for Deforestation Monitoring in the Brazilian Legal Amazon
PES	Payment for Ecosystem Services
PCI	Produce, Conserve, Include
Pixel	The minimum size area on the ground detectable by a remote sensing device
REDD+	Reducing Emission from Deforestation and forest Degradation, “+” signifies the role of conservation, sustainable management of forest and enhancement of forest carbon stocks.

SMBYC	National Forest Monitoring System
TMF	Tropical Moist Forest
JRC	Join Research Center
USGS	United State Geological Survey

GENERAL INTRODUCTION

BACKGROUND

Tropical forests cover the equatorial region, extending from the Tropic of Capricorn to the Tropic of Cancer. Their total area in 2020 was roughly 1 070.9 Mha, which included undisturbed and degraded forests (Vancutsem et al., 2021). With the greatest concentrations of plant and animal species on Earth and vital ecosystem services, the tropics are vital to the planet's ecology (Mittermeier et al., 1998; Myers, 1988). Tropical forests (evergreen forests), are especially important for controlling the world's temperature, carbon storage, preventing soil erosion, preserving the hydrological cycle, and supplying timber and non-timber products to the local inhabitants that rely on them are some of their roles (Brandon, 2014).

Deforestation globally is mainly caused by agricultural land expansion to meet the higher demand for products such as soy, oil palm, cattle, and subsistence crops. Whereas global value chains account for 20–25% of global deforestation, domestic demand for beef and cereals account for 70–80% of this deforestation (Pendrill et al., 2022). Alarming, one-third to half of the deforestation for agriculture does not result in productive land but is caused by land speculation, unclear land ownership, and poor land management. According to Foley et al. (2005), the clearing of cropland and pastureland in an effort to meet the increasing global demand for food has been the primary cause of tropical forest land-use/cover change.

In Brazilian Amazon, the process accelerates as forests are rapidly being changed into extensive agriculture, fueled by infrastructure development, insecure property rights, and high demand levels for pasture for cattle ranching and crops like soybeans (Rudel et al., 2009). The intersection of global drivers—international market forces—and local processes, including land-use policy and road expansion, greatly enhance forest loss. The result not only enhances climate impacts but also diminishes biodiversity. To effectively deal with this crisis, we must accord top priority to rural development and territorial governance approaches that ensure sustainability. The way forests change

over time is largely shaped by three key processes: deforestation, where trees are cut down; forest degradation, which refers to the decline in forest quality; and regeneration, the process through which forests recover (Lambin et al., 2003; Lapola et al., 2023; Vancutsem et al., 2021). These changes reveal the complex challenges we face in managing tropical ecosystems. They highlight the intricate relationships between our actions as humans and the natural world, underscoring the need for careful stewardship of these vital environments.

Satellite monitoring reveals that between 1990 and 2019, tropical forest lost 218.7 million hectares (17%), out of which approximately 1,071 million hectares remained, with 10% of these areas presently degraded (Vancutsem et al., 2021). Pacheco et al. (2021) mention in your study that the Amazon has been split into five separate fronts: Brazil, Colombia, Peru, Bolivia, and Venezuela (Fig. 1). Brazil remains the deforestation hotbed of the Amazon, driven primarily by large-scale cattle ranching and soybean crop expansion. Deforestation has accelerated sharply in Colombia in recent years, primarily due to land grabbing and speculative clearing following the signing of the peace agreement. Peru is plagued by extensive deforestation because of small-scale agriculture, illicit gold mining, and new road networks into out-of-the-way areas. Bolivia has seen a rapid rise in deforestation areas, primarily in its lowland dry forests, brought about by large-scale mechanized agriculture. Venezuela's Amazon rainforest is ever more plagued by illegal mining and widespread burning, increasing forest loss with limited environmental regulation.

While Brazil succeeded in reducing annual deforestation from peaks of 3.5 million hectares per year in the early 2000s to lower levels in the following decade, the past five years have witnessed a marked increase in total disturbances, particularly in degradation (Vancutsem et al., 2021). This shift highlights the increasing significance of non-clearance drivers of forest loss, including fires and edge effects, which are often overlooked in traditional deforestation monitoring. Thus, even as there has been improvement in reducing clear-cut deforestation, the overall cohesion of Amazonian forests

continues to be threatened by cumulative drivers, and what is needed are integrated policies that address both deforestation and degradation. In the case of deforestation, the overall cohesion of Amazonian forests continues to be threatened by cumulative drivers, and what is needed are integrated policies that address both deforestation and degradation.

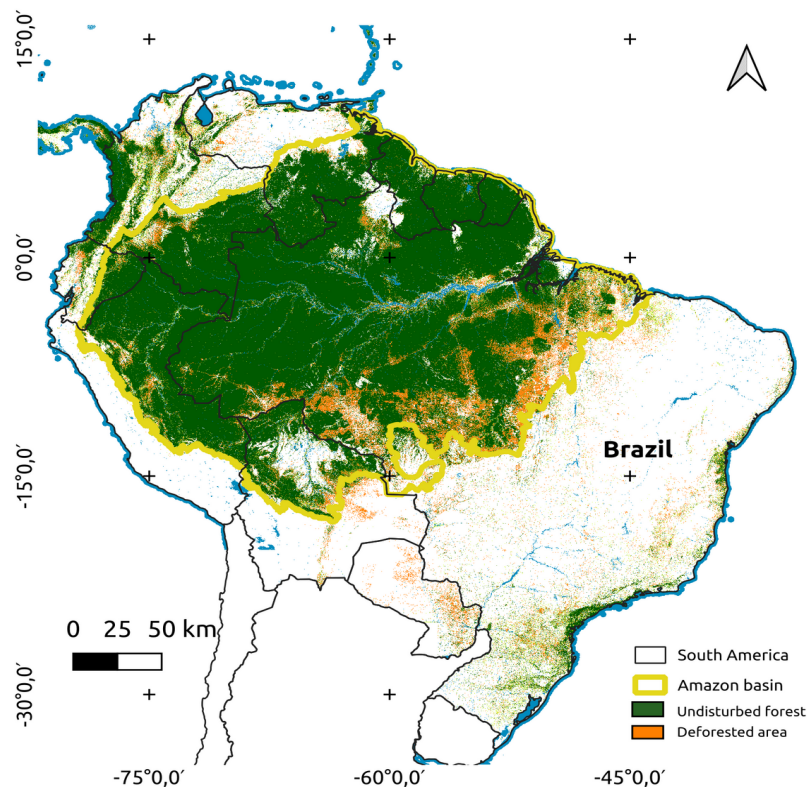


Figure 1: Spatial distribution of tropical forest across Amazonian countries. Adapted from Vancutsem et al. (2021).

KEY CONCEPTS LINKING PROCESSES AND INDICATORS OF FORESTS COVER CHANGES

Deforestation, forest degradation, and secondary forest transform forest cover into diverse landscapes, particularly along the arc of deforestation of the Amazon Basin, where complex interactions between humans and the environment shape distinct landscape patterns (DeFries et al., 2004).

Deforestation

Deforestation is defined as the long-term conversion of forested land to other land uses (Geist and Lambin 2002; Achard et al. 2014). Deforestation can alter water availability and surface-atmosphere flux of water and energy of tropical forest, especially in the southern of Amazon Basin, which have experienced rapid deforestation in the last three decades (Vourtilis et al. 2008). Deforestation affects ecosystem functioning and biodiversity protection, and it is a contributing factor to global climate change (Brook et al., 2003; Fearnside & Laurance, 2004; Homeier et al., 2013).

In the Amazon, drivers of deforestation are dynamic. Expanding pasture for cattle ranching remains the leading driver of forest conversion. However, its intensity varies by country: it is declining in the Brazilian Amazon, while it continues to rise in Bolivia, Colombia, and Peru. Such work is typically linked to land speculation, whereby forest destruction seeks to establish property rights ahead of productive purposes (Beren guer et al. 2021; Pacheco et al. 2021). Giant agriculture, driven by global commodity demand, invests in previously converted lands as well as advances ranching into new forest fronts (Pacheco et al. 2021). Infrastructure construction—particularly regional roads—increases penetration of remote areas and connects production zones with markets. Besides, small-scale illegal logging, illegal mining—especially gold mining in rivers and floodplains in Peru (Asner and Tupayachi, 2017); and widespread use of burning to clear woody cover after logging are all significant drivers of forest decline and loss (Fearnside et al., 2001). Institutional weakness, tenure insecurity, and pressure on Indigenous and public lands contribute to these risks.

Deforestation has caused several negative effects, including the loss of 1.18 Pg C of biomass in the Amazon basin from 2010 to 2019 (Brienen et al., 2015; Fawcett et al., 2023), increases in land surface temperature (Li et al., 2016), soil erosion (An et al., 2022), carbon loss due to edge effects (Silva et al., 2020), fragmentation (Singh et al., 2017; Tapia-Armijos et al., 2015), changes in the regulation of water balance and river flow (Foley et al., 2007), and loss of plant and animal biodiversity (Gibson et al., 2011).

The Brazilian Amazon has lost approximately 22% (84.91 million hectares) of its original forest cover. However, deforested areas are often followed by the emergence of secondary forests, which are part of a rotational system aimed at restoring soil nutrients through land abandonment. This process is also influenced by market access (Zarin et al., 2001). As of 2017, approximately 12 million hectares of secondary vegetation were reported in Brazil (Nunes et al., 2020).

Forest Degradation

Another process is forest degradation, which is defined as the alteration of the structure and composition of forest cover by anthropogenic actions such as selective logging and understory fires (Asner et al., 2005; Matricardi et al., 2010). Different types of forest degradation depend on the accumulation and intensity of anthropogenic disturbances in time and space that partially destroy the canopy without causing a change in land use (Bourgoin, 2019; Tritsch et al., 2016). According to Bustamante et al. (2016), degraded areas in tropical regions are frequently dynamic areas in transition and may follow various paths depending on the severity, frequency, and scope of the disturbance episodes. Forest degradation can also be understood as the reduction in a forest's capacity to provide ecosystem services caused by natural disturbances and, mainly, anthropogenic activities (Bustamante et al., 2016). The degradation of forest cover has consequences such as increasing vulnerability to fire, doubling net carbon emissions in drought events such as the Niño phenomenon (Aragão et al., 2014), producing edge effects and isolated forest patches (Broadbent et al, 2088; Brinck et al., 2017), and altering the water balance and loss of biodiversity (C. Nobre et al., 1991; C. A. Nobre et al., 2016) (Fig. 2).

The changes in forest cover induced by processes of forest degradation and deforestation have a significant impact on the reduction of carbon stocks in tropical forests and serve as a major source of CO₂ emissions into the atmosphere (Baccini et al., 2012; Blanc et al., 2009; Sasaki et al., 2016). Selective logging also impacts the dynamics and ecosystem services of tropical

forests; in these logging areas, energy and water flows are primarily affected due to changes in albedo caused by high levels of canopy openness from felled trees, particularly in the short term (1 to 3 years) (Huang et al., 2020). These practices also contribute to increased temperature within the forest, wind exposure, and humidity deficits (Laurance et al., 2011; Mollinari et al., 2019). The cumulative effects of these disturbances can even hinder the recovery of biomass for the second cycle of timber extraction.

Forest degradation in the Amazon increased by 112% between 2001 and 2018, affecting a total area of 364 748 km² (Lapola et al., 2023). Among the main drivers of forest degradation, edge effects extended over 188 531 km², while logging affected 119 700 km² and fires impacted 122 624 km². In addition, droughts extended over 2 740 647 km² during the same period (Lapola et al., 2023). Similarly, other studies indicate that forest degradation reached levels equal to or surpassing deforestation in the Amazon Basin (Aragão et al., 2018; Bullock et al., 2020).

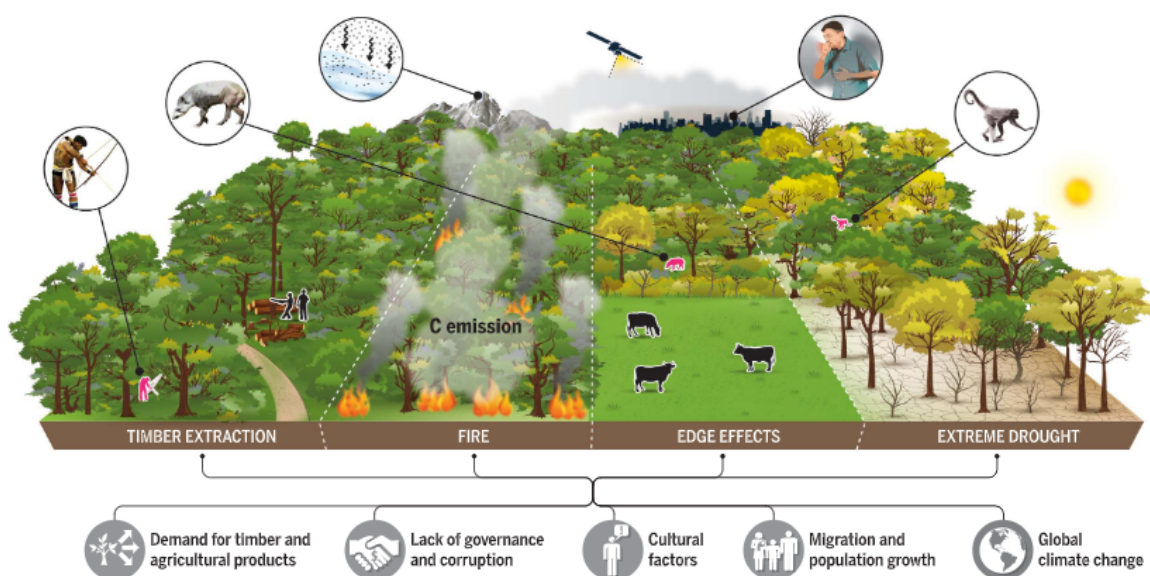


Figure 2: An overview of tropical forest degradation processes in the Amazon basin (Source: Lapola et al. 2023).

Regrowth

Forest regrowth is defined as the reestablishment of forest cover by natural or artificial means after the elimination of the previous cover due to deforestation

(TBFRA, 2000). In the tropics, there are a growing number of large-scale studies of forest regeneration (Brancalion et al., 2012). For example, the expansion of forest regeneration in Colombia (Etter et al., 2005) and Brazil (Perz et al., 2010) in the periods of 1990 and 2010 was characterized by areas associated with agricultural crops or grazing areas, which originated from a process of deforestation and subsequently abandoned or reforested for timber production and watershed conservation (López & Rothlisberger, 2011).

Amazonian secondary forests contribute considerably towards meeting national and global restoration goals, such as the Paris Agreement and Sustainable Development Goals related to food security, climate, water, health, and biodiversity (Bustamante et al. 2019). However, restoration of the Amazonian forest currently has been much less than required, given current rates of ecosystem loss and climate change (Gatti et al. 2021). The Amazon biome lost 13% of its old-growth forest through deforestation by 2017 (Smith et al. 2021). Better governance is needed to reverse forest loss and recover large areas, including institutional action, and the role of the local actors in decision-making.

Secondary forests also play a significant role in tropical forest dynamics. Between 1990 and 2020, 2.31 million hectares of secondary forests were identified in Colombia, and 10.67 million hectares in Brazil (Vancutsem et al., 2021). These areas are crucial for biodiversity conservation and contribute significantly to carbon storage, underscoring their ecological and climate-regulating importance.

Deforestation, forest degradation, and forest regeneration are interconnected processes that contribute to the formation and evolution of pioneer fronts in the Amazon. The processes do not work individually: they interact with each other in certain areas, modifying the landscape structure and creating spatial patterns characteristic of each pioneer front (Schielein and Börner, 2018). In expansion fronts, initial forest clearing and subsequent forest degradation occur prior to the arrival of the agro-frontier, whereas in consolidated fronts, forest regeneration takes place along agricultural matrices. One does not

recognize the process of transition from forest in its natural state to anthropized landscape where the frontier not only advances but also redrafts itself without an understanding of processes interacting.

The relationship between these processes and pioneer fronts is evident in concrete changes to the territorial configuration. This configuration redefines the landscape's architecture, reducing forest connectivity, shaping productive matrices, and increasing the flammability of degraded forests during droughts. Pioneer fronts, far from being mere “deforestation fronts,” are areas that are shaped by these three processes, where trajectories depend on local factors (Schielein and Börner, 2018): such as land tenure (Pacheco and Meyer, 2022), agriculture (soybeans, livestock), and governance frameworks. Failing to consider this complexity leads to weak policy: addressing deforestation alone without considering forest degradation or downplaying regeneration is tantamount to omitting land use systems in pioneer fronts.

LITERATURE REVIEW ANALYSIS OF FOREST COVER CHANGES

Land use systems in pioneer frontiers

The concept of the pioneer frontier is well-established in geography. It is defined as a moving boundary that separates uninhabited areas from those with settlements (Turner & Bogue, 2010). In Brazil, MONBEIG (1952) defines the pioneer strip as the continuous movement of demographic and economic expansion, driven by the construction of cities, roads, and agricultural fields. The expansion of the agricultural frontier in the Amazon is a complex phenomenon, where land speculation through private colonization projects is dynamic in both space and time (Philippe, 1986). The frontier is a territory where interactions between social actors create a variety of landscape mosaics. These frontiers can be either active or inactive (Dubreuil et al., 2008; A. Rodrigues et al., 2009).

A foundational study addressing the relationships in frontier landscapes is the work of DeFries et al. (2004), who propose a landscape analysis for monitoring pioneer frontiers. In their approach, land-use changes follow a series of stages, shaped by complex interactions between economic development and the ecological characteristics of the landscapes. They define five successive stages of frontier progression, based on the extent of landscape occupation (Fig 3):

- Pre-settlement phase: This initial phase is characterized by the land primarily being covered by forests, with little to no human activity.
- Occupation stage: The occupation phase begins with the arrival of the first settlers, who start clearing the forest, typically for timber production or subsistence farming.
- Consolidation stage: This stage is marked by a large portion of the population shifting towards food production for human consumption, solidifying agricultural practices.
- Intensification phase: The intensification phase starts when small-scale farms are replaced by large estates dedicated to growing staple crops, marking a shift toward more commercial agriculture.
- Intensive phase: This stage is characterized by a large proportion of agricultural land being cultivated intensively. Furthermore, the development of profitable agriculture attracts new immigrants, fueling rapid urbanization.

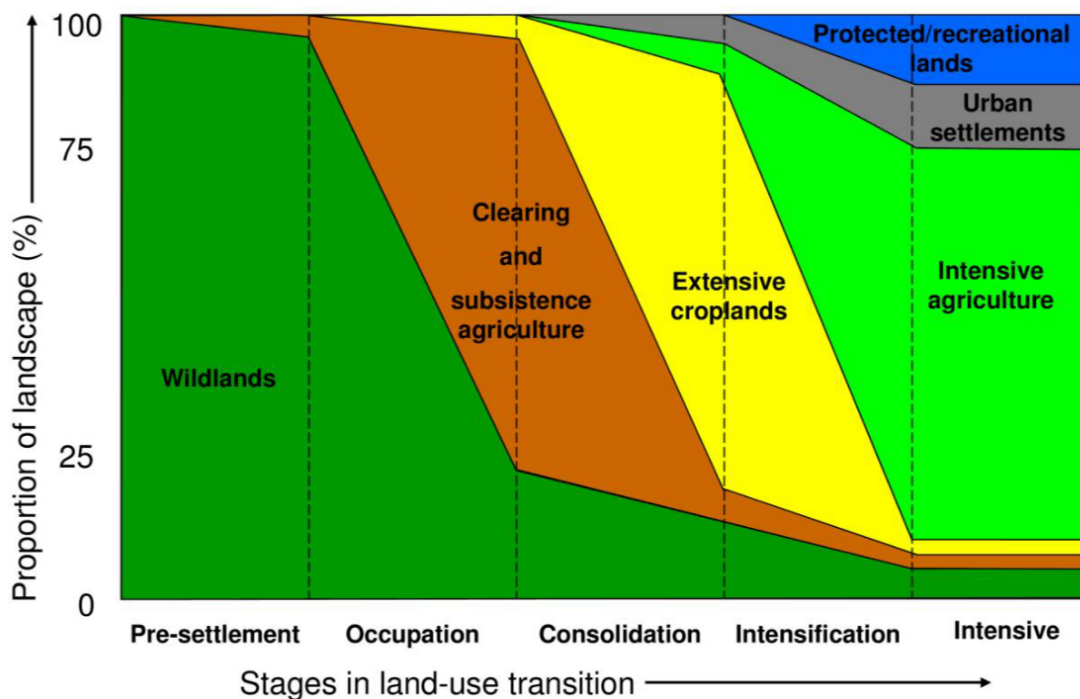


Figure 3: Different stages in land-use transition along the pioneer frontier. Source: DeFries et al. (2004).

Another study that relates spatial and temporal patterns in the Amazon deforestation frontier is that of Rodrigues et al. (2009). Their research focuses on analyzing the different phases of deforestation trajectories at the municipal level. The study defines

five classes based on human development index and the extent of deforestation over time.

- **Pre-frontier:** Characterized by areas with no deforestation.
- **Early frontier:** In this phase, deforestation is active, but a significant portion of forest cover remains.
- **Peak frontier:** This stage is marked by very active deforestation and intermediate levels of forest cover
- **Late frontier:** Deforestation continues to be active, and most of the forest has already been lost.
- **Post-frontier:** Characterized by no further deforestation, with little to no forest cover remaining.

The deforestation process began with government-led colonization plans along the eastern and southern borders of the Amazon in the states of Rondônia and Mato Grosso in the early 1970s. By the 1980s, it extended westward into the state of Pará, forming a "deforestation arc" that continues to expand toward the heart of the Amazon.

The DeFries and Rodrigues studies have significant limitations for addressing the complexity of socio-ecological transitions in the Amazon. First, their approach focuses almost exclusively on deforestation as a separate process, ignoring the significance of other key processes such as forest degradation and regeneration. Second, their models operate at Amazonian scales, which obscures the underlying heterogeneity in land-use change trajectories. For example, while a transition to intensive agriculture (soy and technified livestock) is observed in southern Pará, family agriculture and extractive production systems persist in other regions, such as northern Mato Grosso. This variety of trajectories challenges the linear and universalistic perspective of transition (forest to extensive/intensive agriculture) proposed by DeFries. In face of these limitations, the archetype approach emerges as a theoretical and methodological imperative. By classifying the territory into typologies based on the combination of multiple processes (deforestation, degradation, regeneration), my research uses this framework to develop forest cover indicators that reflect not only forest loss but also landscape heterogeneity,

thus providing a more comprehensive vision for the sustainable management of change fronts in the Amazon.

Archetype approach

Understanding the complex interactions between people, land use, and the environment is one of the primary challenges in earth system science (Rounsevell et al., 2012). Archetypes are used as a methodological approach to comprehend patterns of variables and processes that shape the sustainability of socio-ecological systems across different time and spatial scales (Jäger et al., 2007; Messerli et al., 2015). Archetypes can be existing taxonomic or landscape units, or new combinations of landscape attributes developed for a specific purpose (Cullum et al., 2017). Additionally, archetypes provide valuable information for transferring different management approaches to areas with similar characteristics. The concept of land-use archetypes was developed in response to the need to incorporate multiple dimensions of land-use intensity in socio-ecological systems (Václavík et al., 2013). This approach has been used to identify the heterogeneity of vulnerability in agricultural systems in drylands in Africa (Sietz et al., 2017).

Archetypes have been used at a global scale to identify and map deforestation frontiers in tropical dry forests (Buchadas et al., 2022). At a regional scale, they have been applied to describe frontier processes in deforestation hotspots within a dry forest ecoregion in South America (Baumann et al., 2022).

Archetypes are particularly relevant for analyzing Amazonian pioneer fronts because they capture the heterogeneity of processes underlying the boom-and-bust pattern described by Rodrigues et al. (2009). While the original study identified the boom and collapse phases, archetypes allow these processes to be broken down into specific typologies. Each archetype reflects a particular combination of deforestation, degradation, and regeneration dynamics, which helps explain the homogeneous view of the pioneer frontier and reveals how development trajectories depend on complex interactions in each territory.

The archetype approach adds a complementary analytical focus to Defries et al. (2004) (phases of land use transition) and Rodrigues (boom-and-bust trend) frameworks by broadening them explicitly to involve the spatial, temporal, and multifunctional dimensions of socioecological change. Whereas DeFries highlighted generic sequences of change (from forest to subsistence agriculture and

intensification), and Rodrigues combined human development index, archetypes allow these patterns to be mapped and measured simultaneously. Thus, archetypes localize actions in the territory as a spatially explicit diagnostic tool for deriving context-specific policy.

Landscape metrics

It is crucial that landscape metrics be used in the characterization and understanding of the ecological and anthropogenic processes that occur within land-use change archetypes since they allow the quantification of spatial patterns. While archetypes delineate socio-ecological trajectories, landscape metrics such as edge density, largest patch index, mean patch area, or patch number portray the spatial distribution of forest cover in each archetype. By incorporating landscape metrics, policies differentiated by and priority conservation actions (i.e., connectivity corridors within fragmented landscapes) can be aimed at the territorial design. Landscape metrics thus present to us the quantitative vocabulary in which to disentangle the intricacy of each archetype and associate spatial forms with processes and present a sound basis for adaptive land management.

Tropical forest landscapes have been heavily modified by human activity. Starting in the 1980s, with the advent of Geographic Information Systems (GIS), indicators for measuring patterns and landscape metrics began to be proposed using raster data (Krummel et al., 1987; O'Neill et al., 1988, 1996). Today, several programs are available that can automatically calculate landscape metrics (Baker & Cai, 1992; Hesselbarth et al., 2019; McGarigal, 1995). These tools have been applied in landscape monitoring (Sachs et al., 1998; Simpson et al., 1994), biodiversity planning and conservation (Pardini et al., 2010), as well as in identifying fragmentation in tropical forests and its relationship with the composition and structure of forest remnants (Meza Elizalde et al., 2018).

The use of landscape metrics has been widely applied. Uuemaa et al. (2013) propose grouping them into four general categories: a) for the evaluation of land use and land cover patterns; b) biodiversity and habitat analysis; c) regulatory functions; and d) informational functions.

- a) Evaluation of land use and land cover patterns: Different configurations of landscape metrics have been proposed for landscape planning and monitoring (Botequilha Leitão & Ahern, 2002; Schindler et al., 2008). Landscape metrics are

suitable for detecting deforestation and forest degradation quickly at regional and global scales (Alves et al., 2021; Brinck et al., 2017).

- b) Biodiversity and habitat analysis: Various studies have evaluated the relationship between landscape metrics and the spatial distribution of bird species (Miller & Conner, 2007), mammals (Martínez et al., 2010; Schindler et al., 2008), and insects (Gaines et al., 2005; Graham et al., 2004; Kie et al., 2002), as well as the impacts of fragmentation on species distribution and richness (Honnay et al., 2003; Yang et al., 2008). Additionally, landscape metrics have been used to assess the fragmentation or connectivity of tropical forests (Metzger, 2002; Murillo-Sandoval et al., 2022; Ritter et al., 2021).
- c) Regulatory functions: As an important indicator for determining water quality, the landscape composition in terms of cover proportion has demonstrated its significance in regulatory services (Gergel et al., 2002; Moreno, 1996). Since the type of cover and the degree of fragmentation in the landscape determine the severity of a fire, measuring fragmentation is crucial for fire risk reduction management and planning (Lee et al., 2009). The size of forest patches affects the ability of forests to provide ecosystem services; consequently, smaller forest patches are more susceptible to edge effects and increased fragmentation (Fischer et al., 2021).
- d) Information functions: It has been demonstrated that there is a connection between landscape structure and visual perception. People tend to prefer heterogeneous and open landscapes where water is present (Dramstad et al., 1996; Tveit, 2009). Additionally, the metrics of landscape composition and configuration can be considered as landscape indicators because they are related to people's landscape preferences (Dramstad et al., 2006).

A NEW CONCEPTUAL MODEL OF FOREST COVER CHANGE

A conceptual model of the direct and indirect drivers of deforestation in tropical forests was proposed by Geist and Lambin (2001). Despite its broad scope, the conceptual framework for forest cover change developed by Geist and Lambin (2001) does not explicitly incorporate the role of institutions, which are critical levers in enabling the impact of forest governance on Amazonian territories. To address the shortcomings of the original model and better capture the region's

specific dynamics, this study introduces two key enhancements. To begin with, it broadens the range of outcomes examined to encompass not just deforestation but large-scale processes like forest degradation and regeneration. I propose a conceptual model at a subnational scale, which includes geographic zones such as Paragominas and Cotriguaçu in Brazil and Guaviare in Colombia. This approach acknowledges the complex and often non-linear nature of ecological change. Second, and as a fundamental innovation, an institutional aspect is brought to the fore.

This adapted model, represented conceptually in (Fig.4), posits that underlying or indirect causes, such as population growth, road network expansion, livestock farming, agriculture, and legal frameworks, do not act autonomously. Rather, they are filtered, facilitated, or constrained by an ensemble of institutions and policies. Institutional colonization, state laws, government agency action such as INCRA (Institute for Colonization and Agrarian Reform), and the constitutional framework directly determine the nature of these drivers in the territory. These institutionally mediated underlying causes contribute to the proximate causes of deforestation and degradation, which in turn are modulated by biophysical factors such as topography, soil type, and the occurrence of droughts.

The result of these complex interactions is changing the condition of the forest, assessed both in its superficial extent (net area) and in its organization and operation (ecological integrity). This integral model enables a more comprehensive analysis of the transformation processes in Amazonian territories. We thus propose in this study, a revision of the model proposed by Geist and Lambin (2001) that incorporates deforestation, forest degradation, and regeneration (Fig. 4).

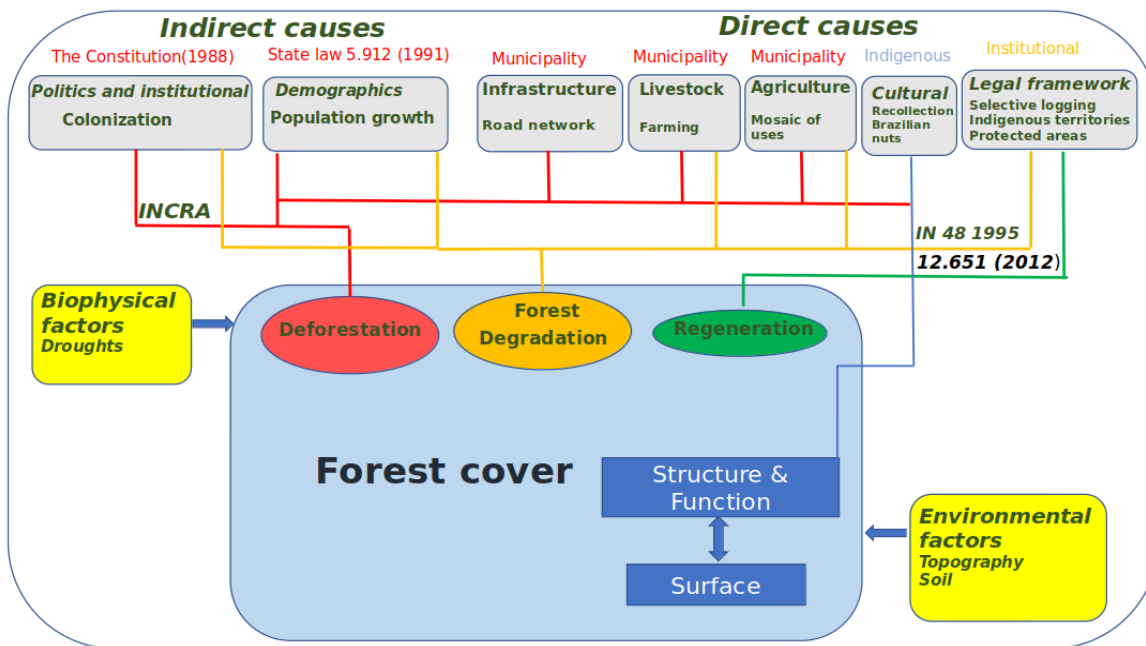


Figure 4: Relationships between direct and indirect causes of disturbances, processes (deforestation, degradation and regeneration) and their consequences for forest cover change. These consequences can be assessed via indicators related to area, structure and function and ecosystem services and the interactions among these three modalities. For example, a rural migration (indirect cause) can lead to the abandonment of agricultural land (direct cause) and promote forest regeneration (process), which can be measured by several indicators, such as changes in secondary forest area or changes in carbon stocks (ecosystem services). Modified from Geist & Lambin (2001).

RESEARCH QUESTION AND OBJECTIVES

The forest cover changes in the Amazon regions are governed by these three processes: deforestation, forest degradation and regrowth. This has generated forest landscapes with complex structures and functions, especially in the deforestation arc. However, the trajectory of this landscape has only been measured through deforestation as the only indicator over time. Against this background, we propose the following general objectives:

- **Identifying indicators related to forest cover change will help forest cover management at a territorial scale.**
- **Evaluating how forest cover processes in the Amazon create diverse forest landscapes and the consequences**

Two research question and one operational research question are derived from this (Fig. 5):

RQ1: How can landscape units reflecting the transformation processes of deforestation, degradation and regeneration be stratified?

RQ2: What is the relationship between transformation processes and changes in landscape structure (composition and configuration), fire dynamics and legal territorial designations?

RQ3: How can landscape change analysis help us identify indicators of forest cover change that are useful for decision making?

To answer this questions, we chose to rely on the revised version of Lambin's conceptual model (Fig 4) which provides a robust analytical framework to integrate ecological, spatial, and institutional drivers of forest cover changes. The research adopts an original methodological approach that combines forest trajectory analysis with landscape metrics to identify archetypes according to their deforestation, degradation, and regeneration dynamics. This framework was tested in three contrasting subnational jurisdictions within the Amazon Basin over the period 1991–2020. Medium to high resolution geospatial information (30 m) were utilized to capture fine-scale landscape diversity to enable more accurate territorial scale analysis. Such spatial forms were also interpreted additionally through a participatory approach comprising stakeholder workshops and semi-structured interviews to embed local knowledge and perceptions. This hybrid methodology not only enhances the analysis of forest landscape dynamics but also contributes to the design of spatially explicit indicators to enable more adaptive and inclusive forest management.

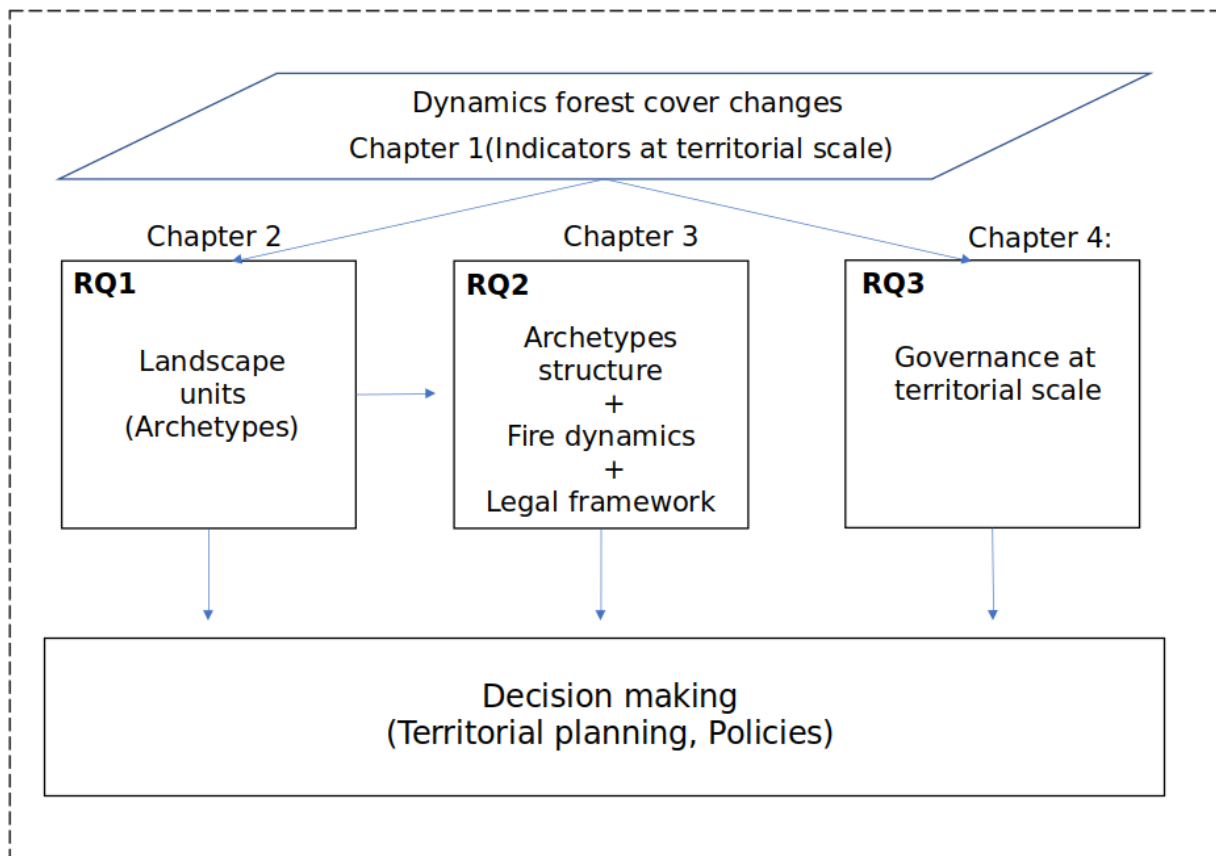


Figure 5: Overview of the thesis structure with the sub-research questions and respective chapters linking forest cover change dynamics and territorial analyses for territorial planning and policy support.

STRUCTURE

This PhD thesis is organized into four chapters. Three result chapters (Chapters 2 to 4) are structured as scientific articles, each addressing different research questions (R1 to R3).

Chapter 1 identifies the available indicators for monitoring forest cover change dynamics at the territorial scale. In this chapter, we provide a description of the study sites and utilize national data sources from each subnational jurisdiction, along with international datasets available for monitoring forest cover changes. The indicators considered include deforestation, forest degradation, secondary forests, fire, and precipitation.

Chapter 2 focuses on the identification of homogeneous units resulting from forest cover changes in subnational jurisdictions of the Amazon. We integrate spatial and temporal information on three key processes deforestation, forest degradation, and regeneration to identify and classify homogeneous units

(archetypes) at the territorial level in Guaviare, Paragominas, and Cotriguaçu. The Kamila algorithm is used to classify mixed data (continuous and categorical) from nine metrics. This approach ensures adaptability to different datasets and effectively represents the spatiotemporal dynamics of forest cover change.

Chapter 3 examines the composition and configuration of archetypes across the three subnational jurisdictions: Guaviare, Paragominas, and Cotriguaçu. This chapter analyzes land-use changes dynamics by archetype, using land-use and land-cover data to identify transitions and landscape metrics. Additionally, we incorporate information from the territorial regulatory framework to assess the distribution of archetypes. The discussion focuses on land-use change characteristics, land-cover transitions, and the identification of different forest cover management actions based on the archetypes and the territorial regulatory framework.

Chapter 4 presents a methodological approach developed to identify relevant forest cover change indicators through the participation of local actors in the municipality of Cotriguaçu. This approach is based on semi-structured interviews with different types of local actors to capture a comprehensive perspective on forest cover change dynamics, considering deforestation, forest degradation, and regeneration processes. Additionally, two participatory workshops were conducted to identify key aspects of institutional capacity for implementing restoration projects in permanent protection areas at the municipal level, aiming to enhance forest governance and ensure the sustainable management of forest resources.

CHAPTER 1- STUDY SITES PRESENTATION: WHAT PUBLIC DATA REVEAL ABOUT FOREST COVER DYNAMICS

1.1 Study sites description

The three study sites for this research are located within the Arc of Deforestation in the Amazon, spanning two municipalities in Brazil, Cotriguaçu and Paragominas and the Guaviare department in Colombia's Amazon region (Fig. 6).

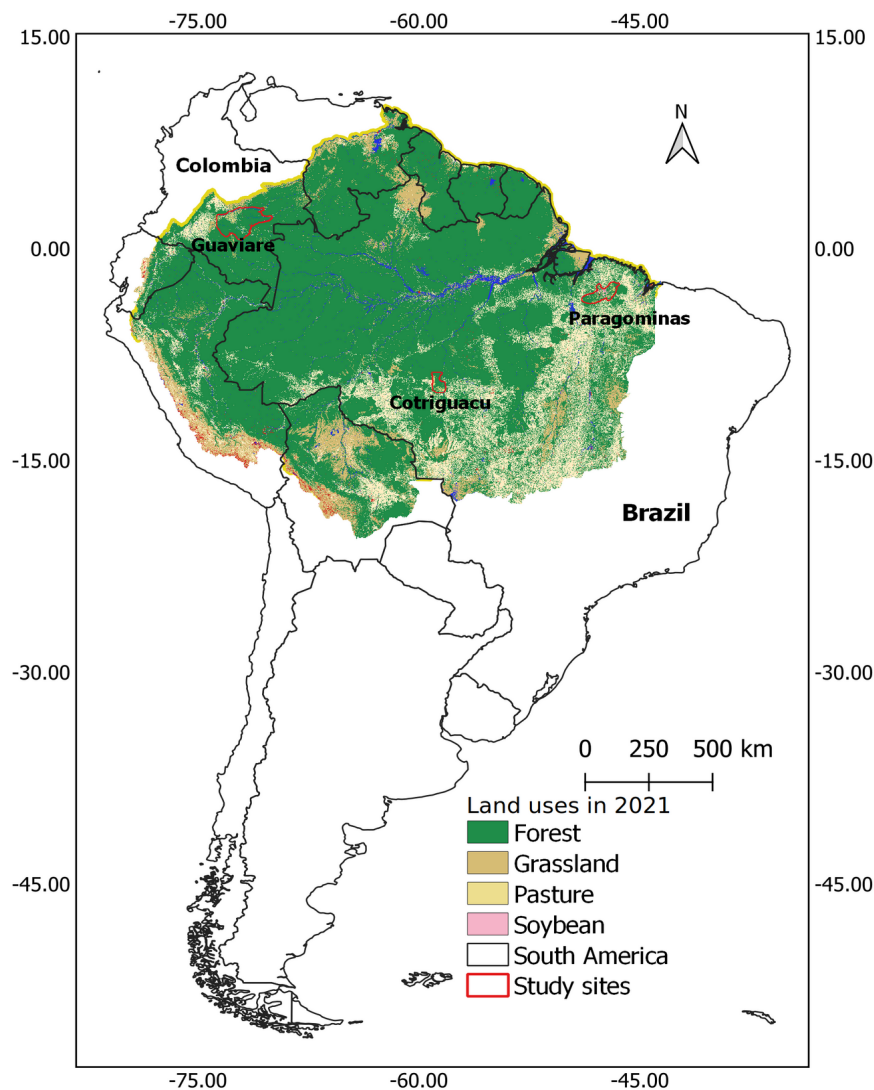


Figure 6: Study sites (red lines) located in human-dominated tropical landscapes of deforestation fronts. (source: Mapbiomas 2021).

These three sites exhibit diverse landscapes, shaped by complex processes of colonization, land occupation, and forest cover change dynamics (Table 1). These territories are part of the TerrAmaz project (<https://www.terramaz.org/>), an initiative aimed at supporting local stakeholders in transitioning toward

improved forest resource management and sustainable livelihoods in the Amazon.

The three study areas show distinct demographic and economic profiles. Guaviare is the largest territory (53 460 km²) with a low population density of 1.72 inhab./km² and the highest Human Development Index (HDI) among the cases with 0.74 (Table 1). In contrast, Paragominas presents the highest population density 5.45 inhab./km² and the highest Gross Domestic Product (GDP), reaching 6 429 USD per capita, reflecting a more consolidated economic structure. Cotriguaçu, with the lowest population density 1.21 inhab./km², stands out for having the highest deforestation rate 21% of the territory between 1991 to 2021, suggesting increasing land conversion pressures despite lower demographic pressure.

From an environmental standpoint, Guaviare receives moderate annual rainfall 2 689 mm, while Paragominas is the driest region 1 693 mm, and Cotriguaçu falls in between. Elevation ranges are broader in Cotriguaçu and Guaviare, potentially influencing vegetation distribution and land use suitability. All sites share similar dominant land cover types, such as undisturbed and degraded forests. However, soybean cultivation, a proxy for agricultural intensification, is exclusive to Paragominas. These contrasts highlight different trajectories of territorial occupation and forest landscape transformation across the Amazon frontier.

Table 1: Synthesis of the main characteristics of the three study sites.

	Guaviare (Colombia)	Paragominas (Brazil)	Cotriguaçu (Brazil)	Source
Area (km ²)	53 460	19 342	9 423	DANE, 2018; IBGE, 2021
Habitants (2021)	91 717	105 550	20 717	DANE, 2018; IBGE, 2021
Hab / km ² (2021)	1.72	5.45	1.21	DANE, 2018; IBGE, 2021
GDP (USD)	2 454	6 429	2 717	CDA, 2021; IBGE, 2021
HDI (2021)	0.74	0.65	0.6	CDA, 2021; IBGE, 2021
Rainfall (mm) (1975-2005)	2 689	1 693	2 278	IDEAM, 2017; Andrade, 2011
Elevation (m)	107-427	58-232	117-466	Farr et al., 2007
Deforestation (%)	18.23	14.17	21.55	TMF-JRC

(2001-2021)				
Main land uses	Undisturbed forest, degraded forest, Pasture, Mosaic of uses	Undisturbed forest, degraded forest, Pasture, Soybean	Undisturbed forest, degraded forest, Pasture	MapBiomass (2021)

1.1.1 Guaviare department, Colombian Amazon

1.1.1.1 Geographical conditions

The department's capital, San José de Guaviare, and its surroundings in the north of the region are home to the majority of the population. The department of Guaviare is administratively divided into four municipalities: San José del Guaviare, El Retorno, Calamar, and Miraflores (Fig. 2).

The region is traversed by four major rivers: the Guaviare, Vaupés, Unilla, and Inírida Rivers, all of which are significant tributaries that ultimately flow into the Amazon River basin (Fig. 2). The climate is tropical with an average annual temperature of 25.8 °C and a mean relative humidity of 85%. Average annual rainfall recorded at Guaviare between 1975 to 2005 was 2 689 mm (IDEAM, 2017). The department of Guaviare has a primary paved road, known as "Ruta Nacional 75" which connects San José del Guaviare with Calamar and has a total length of 91 km, representing 6.27% of the total road network in the department (Fig. 7). This road "Ruta Nacional 75" was part of the National Government's initiative to support the substitution of illicit crops and strengthen security policies.

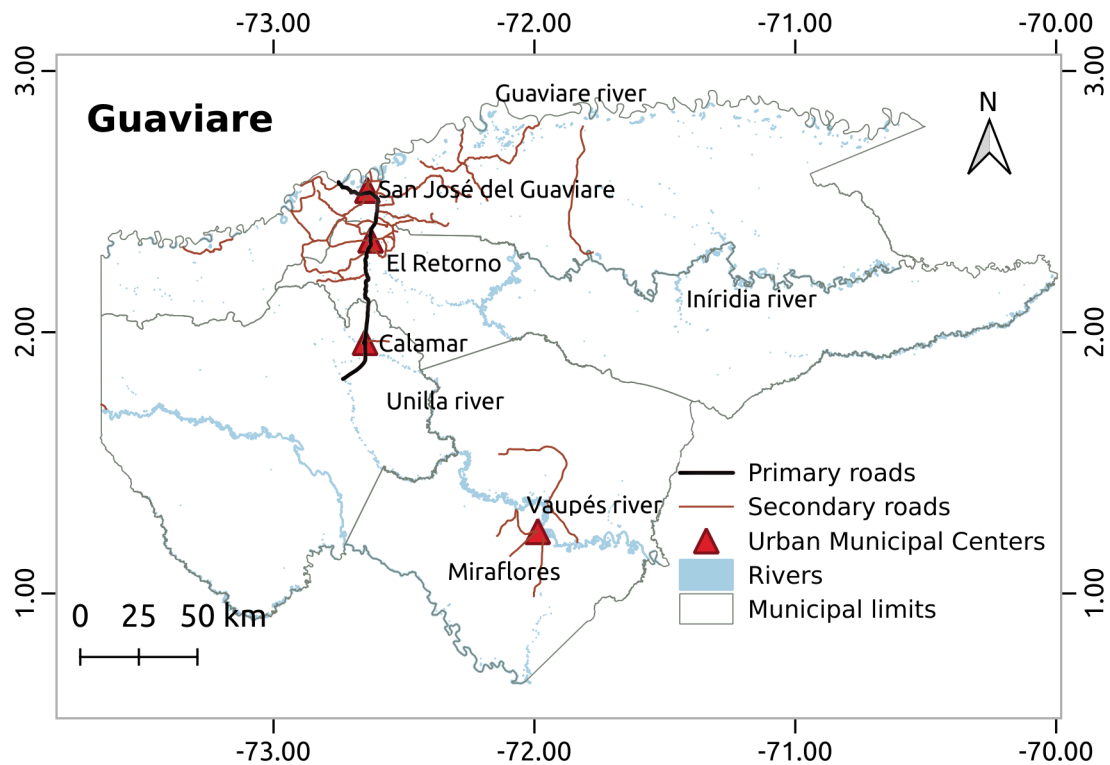


Figure 7: Map of geographical characteristics considering roads, rivers, urban municipal centers in the department of Guaviare, Colombia. Source: <http://www.siac.gov.co/>

Additionally, the department has secondary roads with a total length of 941 km, accounting for 93.70% of the road network. These roads are unpaved, generally in fair condition, and their accessibility is significantly hindered during the rainy season, when transit is often interrupted (CDA, 2015).

The elevation in the department of Guaviare ranges from 107 to 427 meters above sea level (m.a.s.l.) (Fig. 8). In Guaviare, three main soil types are identified: alluvial soils, oxisols, and histosols (IGAC, 2012). Alluvial soils are found in valleys shaped by erosion, where sediment deposition supplies essential minerals for plant growth (CDA, 2015). Oxisols dominate the massif landscape, featuring abrupt topographic elevations with strong lithological control, typically found on moderately to steep slopes (12%–50%) (IGAC, 2012). In the south and west of the department, includes Chiribiquete National Park, La Lindosa, Nukak National Park, and Cerro Paloma, characterized by "Mesas"—flat-topped landforms (CDA, 2015).

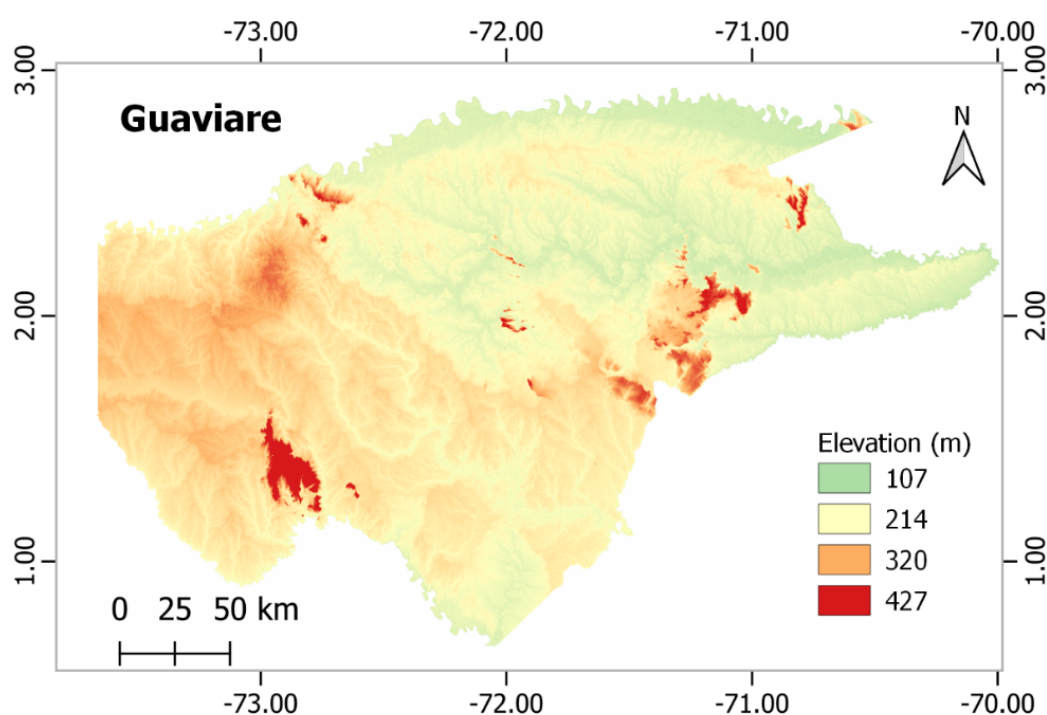


Figure 8: Elevation map of the Guaviare Department, Colombia. Source: (Farr et al., 2007).

1.1.1.2 Socioeconomic characterization

The population of Guaviare was 84 240 inhabitants in 2005, increasing to 91 717 inhabitants by 2021, with an average annual growth rate of 0.55% during this period and a population density of approximately 1.72 inhabitants per km² (DANE, 2018). The department's population is currently 44.3% rural and 55.7% urban (DANE, 2021). Indigenous communities represent 1 089 inhabitants, accounting for 1.19% of the total population (CDA, 2015).

To Guaviare Gross Domestic Product (GDP) per capita was estimated at \$2 454, reflecting low levels of local production (CDA, 2021). Livestock farming is a key economic activity, with 225 000 cattle grazing over an area of 4 300 km² (CDA, 2015). Additionally, the main agricultural activities include the cultivation of cacao, cassava, maize, and rice, covering approximately 15 000 hectares.

1.1.1.3 Legal territorial designations

The department of Guaviare, Colombia, is predominantly composed of national parks and indigenous reserves, covering 19 788 km² and 16 244 km², respectively. Together, these two categories account for 64.3% of the total

territory. Following these, the forest reserve and private properties occupy 15 179 km² and 4 800 km², representing 27.1% and 8.57% of the department's area, respectively (Fig. 9). Guaviare is home to two National Protected Areas: Serranía de Chiribiquete and National reserve Nukak. It also includes 26 Indigenous Reserves, officially designated as: Arara, Barranco Colorado, Barrancón, Barranquillita, Cachivera de Nare, Caño Negro, Centro Miraflores, Corocoro, El Itilla, El Refugio, Guayabero, La Asunción, La Fuga, La Yuquera, Lagos del Dorado, Laguna Araguato, Llanos del Yarí, Morichal Viejo, Nukak Makú, Panure, Puerto Monforth, Puerto Nare, Puerto Viejo, Tucán, Vuelta del Alivio, and Yavilla.

The description, year of establishment, and legal basis for each territorial designation in Guaviare are summarized in Table 2 and their spatial representation across the territory is given in Fig. 9.

The Forest Reserve Zone is a legally designated area established by the Colombian government in 1959 with the objective of conserving Amazonian forests, protecting renewable natural resources, and regulating land use. In the forest reserve, land-use change from forest to other uses is prohibited unless expressly authorized by the State.

The Integrated Management District, established by the Government of Colombia through Decree 1974 of August 3, 1989, is a geographically defined area where traditional productive activities are permitted. In Guaviare, only in the Integrated Management District are properties legally recognized (Fig. 9). In Colombia, private property is constitutionally recognized under Article 58 of the 1991 Constitution, which establishes that property rights are guaranteed but subject to the social and ecological functions of land.

National Parks established under Decree 2811 of 1974, promulgated by the National Institute of Renewable Natural Resources and the Environment, were created with the objective of ensuring strict biodiversity conservation and the protection of ecosystems.

The indigenous reserve constituted by Law 160 of 1994. These laws establish the criteria and procedures for the recognition, delimitation, demarcation, and

titling of Indigenous Reserves. The constitution of these reserves aims to protect indigenous peoples' territorial rights, support their cultural and physical reproduction, and ensure sustainable management of natural resources.

Table 2: Legal territorial designations at the territory scale for the Department of Guaviare-Colombia.

Year	Law	Description	Permitted activities	Source
1959	Law 2 on the National Forest Economy and Conservation of Renewable Natural Resources, Official Diary No. 29861 (1959).	Creates the Amazon Forest Reserve Zone.	Protecting renewable natural resources, and regulating land use.	http://www.siac.gov.co/
1974	Decree 2811 Establishing the National Code of Renewable Natural Resources and Environmental Protection. Official Diary No. 34243. (1974).	Regulates the National System of Protected Areas, and renews the types of areas that compose it. Redetermines the uses permitted in them. Includes Integrated Management Districts in the protected area category.	Protection, surveillance and monitoring	http://www.siac.gov.co/
1989	Decree 1974 Regulating the Article [...] on Integrated Management Districts of Renewable Natural Resources and Law 23 of 1973. Official Diary 38963 (1989).	Regulates processes for creating and zoning Integrated Management Districts of Renewable Natural Resources (Particular property).	Productive activities	http://www.siac.gov.co/
1994	Law 160 Creating the National System of Agrarian Reform and Rural Peasant Development [...] and Enacting Other Provisions. Official Diary 41479 (1994).	Lays down the conditions for the constitution of indigenous reserves. Acknowledges that the property's social and ecological functions	Cultural and spiritual practices: Rituals, community events	https://data-agenciadetierras.opendata.arcgis.com/

can be fulfilled in conformity with the practices, traditions, and culture of its inhabitants.

Finally, in Guaviare, there is a territorial planning entity known as the "Vereda," which is defined in Article 22 of the Community Participation in Territorial Planning section of Law 388 of 1997. The law states that: "Municipal or district authorities may delimit, within the urban perimeter, neighborhoods or groups of residential neighborhoods that are commonly recognized by their inhabitants as local reference points within the city, defining their immediate sense of belonging to a local or neighborhood area. The same principle applies to community participation in defining rural territories, in which case the territorial division will refer to veredas or groups of veredas" (García, 2008; "Ley 388 de 1997," 1997). Currently, 286 "veredas" are registered in the department of Guaviare (Fig. 9).

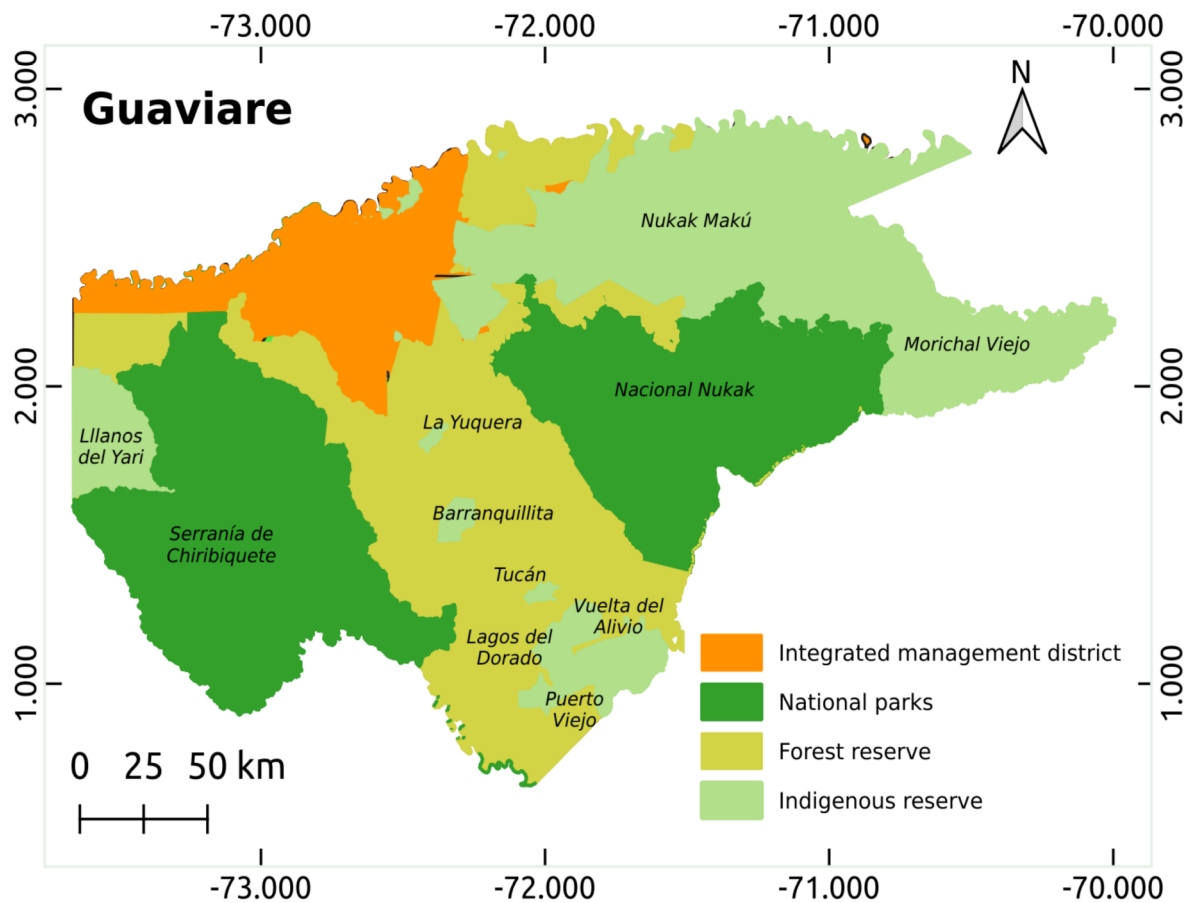


Figure 9: Legal territorial designations in the department of Guaviare, Colombia.
Source: Colombian Environmental Information System <http://www.siac.gov.co/>

1.1.1.4 Historical colonization processes

Guaviare has a complex history of colonization that has taken place in multiple waves. An outline of the major eras and features of colonization in this area is provided below:

- Pre-Columbian period: The area was home to indigenous peoples for thousands of years before European contact, including as the Nukak, Guayabero, and Tucano peoples (Arcila et al., 1999)
- Early European exploration (16th–19th centuries): The area was occasionally visited by Spanish explorers and missionaries, but because of its remote position, colonial settlement was mainly avoided.
- Rubber boom (late 19th–early 20th century): During the Amazonian rubber boom, there was a notable influx of non-native settlers (Arcila et al., 1999). Native American labor was exploited at this time, and certain permanent settlements were founded. In an effort to alleviate population

pressure in the Andean regions and establish authority over isolated areas, the Colombian government promoted colonization of the Amazon region, particularly Guaviare, in the 1940s and 1950s (Salgado Ruíz, 2018). Around the late 1960s, two traditional practices 'tigrilleo', the capture and trade of wild animal skins and fishing, played a central role in driving the expansion of infrastructure and the growth of the population in the department of Guaviare.

- Creation of the department of Guaviare: In 1963, Guaviare was declared a "national territory" and separated from the department of Vaupés. More people were colonizing as a result of government incentives and better road access. In the area, agriculture especially cattle ranching started to grow. Growing coca turned into a significant economic force, attracting additional settlers to the region (Arcila et al., 1999). During 1980 and 2000, drug-related conflicts and significant deforestation occurred. In 1991, Guaviare became a department.
- The reduction of coca cultivation in Colombia is attributed to a combination of state strategies, including manual and aerial eradication policies, the expansion of military presence in rural areas, and alternative development programs. Additionally, institutional strengthening and the expansion of the State's territorial control contributed to limiting the spread of illicit crops in critical regions such as Guaviare. Between 2005 and 2013, the area under illicit crops in the municipalities of San José del Guaviare, Calamar, Miraflores, and El Retorno decreased significantly, from 318 km² in 2005 to 81 km² in 2013 (Fig. 10).
- Guaviare after the 2016 peace accord: There are now new dynamics, experienced a boost in land pressures. Withdrawing armed groups created a vacuum in governance, and land rush went to agricultural expansion, illegal land grabbing, and greater deforestation. It marked the opening of new frontiers of deforestation, predominantly in previously inaccessible areas, following the 2016 peace agreement between the FARC and the Colombian government (Rodríguez-de-Francisco et al., 2021).

Guaviare's colonization reflects larger trends in Amazonian colonization, which emphasize topics like resource exploitation, agricultural frontier development, and the intricate interactions between local reality, political will, and economic pressures.

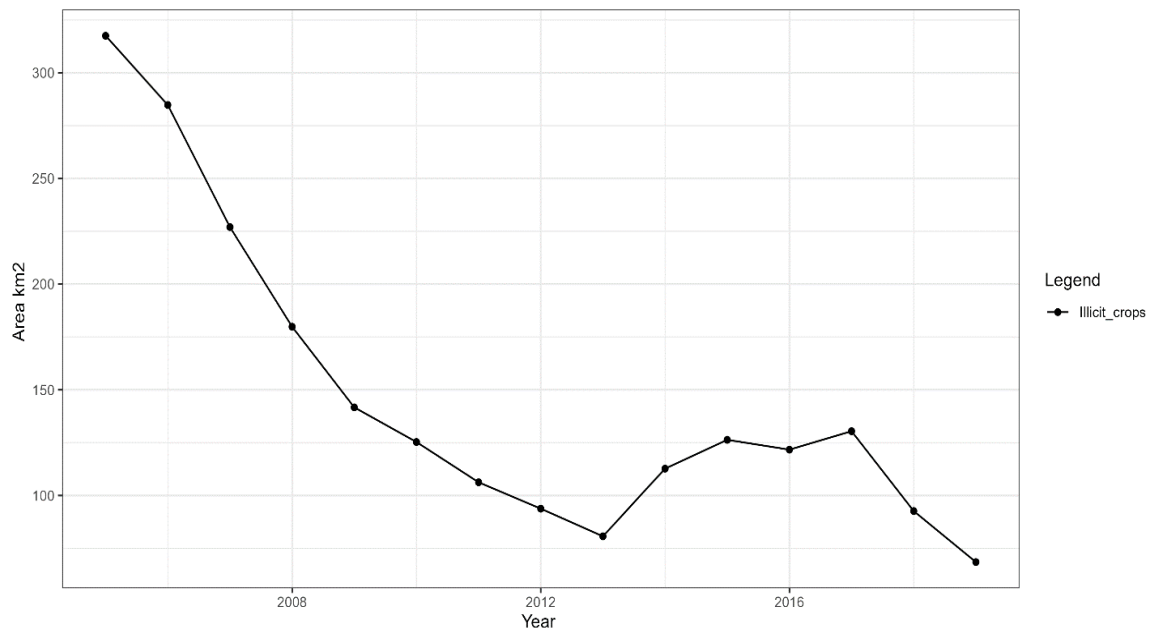


Figure 10: Area of Coca Cultivation from 2005 to 2019 in the department of Guaviare, Colombia. Source: (United Nations Environment Programme, 2016).

1.1.1.5 Problematic of forest cover loss in Guaviare

In Colombia, the peace agreement in 2016 ended the 52-year (1964–2016) conflict between the Colombian state and the FARC (Fuerzas Armadas Revolucionarias de Colombia) guerrilla organization. FARC presence had unintentionally eased pressure on forests, agricultural expansion, and settlement establishment by creating de facto 'off-limits' zones that were inaccessible (Murillo-Sandoval et al., 2020; Rodríguez et al., 2017). Deforestation within protected areas and their buffer zones in Guaviare has accelerated since the peace agreement took effect (Clerici et al., 2020).

The post-conflict transition, while providing for greater mobility and investment, also opened up a power vacuum in the countryside where institutional presence remains fragile. In Guaviare, this vacuum has been filled

rapidly by actors seeking to promote cattle ranching, land grabbing, and illicit crop cultivation, heightening land-use pressures within forest regions (Murillo-Sandoval et al., 2023). As a result, numerous formerly conserved territories, particularly those safeguarded collectively or by the state, have been subjected to accelerated transformation.

To this is added the fragmented and poorly coordinated institutional arrangement for governing land. Programs such as land titling, environmental zoning enforcement, and provision of technical assistance have been implemented patchily, resulting in superposition of claims, legal ambiguity, and poor enforcement capability. This has frustrated the implementation of sustainable land management models and created a gap between policy intention and on-the-ground realities.

In the "Integral Rural Development for Peace in Guaviare - Caminemos Territorios Sostenibles (CTS)" project, efforts were being made to implement sustainable productive systems at the farm level with forest conservation and restoration of degraded areas strategies. As land-use planning in this context is closely linked to the consolidation of these systems, long-term adherence to the productive agreements with farmers was presumed to be an indirect sustainability indicator. This plan was meant to help reduce the growth of agricultural frontiers (Camacho, 2018).

1.1.2 Paragominas municipality, Brazilian Amazon

1.1.2.1 *Geographical conditions*

The municipality is traversed by two major rivers: the Capim River in the west and the Gurupi River in the east (Fig. 11). The average annual rainfall recorded in Paragominas between 1992 and 2010 was 1 693 mm (Andrade, 2011), with a well-defined dry season from may to october, during which mean monthly precipitation remains below 100 mm.

The municipality of Paragominas has two primary paved roads. The first is the Belém-Brasília Highway (BR-010), which extends 74.6 km, representing 1.97% of the total road network in the municipality (Fig. 6). The second is a state highway (PA-125) with a length of 136 km, accounting for 3.59% of the total

roads (Fig. 6). Additionally, the secondary road network has a total length of 3 578 km, representing 94.44% of the municipality's road infrastructure (IBGE, 2019).

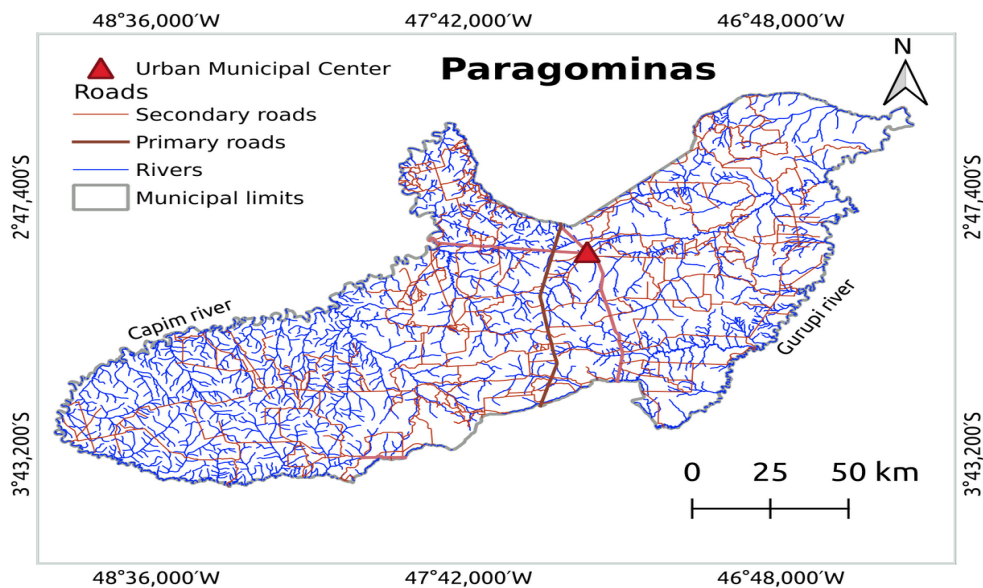


Figure 11: Map of geographical characteristics considering roads, rivers, urban municipal centers in the municipality of Paragominas, Brazil. Source : IBGE, 2022).

The geology of Paragominas consists of Cretaceous to Paleogene sediments, with soils characterized by a superficial Belterra clay layer (Kotschoubey et al., 2005). This soil type has favorable properties for mechanized agriculture and, due to its lateritic crust formation, it is currently exploited for bauxite extraction through open-pit mining (Poccard-Chapuis, 2022). The elevation in Paragominas ranges from 58 to 232 m.a.s.l. (Fig. 12).

The predominant soil types in the region include yellow Latosols and Argisols, with Plinthosols being common, along with small patches of Gleisols and Neosols (Plassin et al., 2017; Rodrigues et al., 2003). The landscape is characterized by a high density of plateaus and valleys, separated by steep slopes, ranging from 50 to 150 meters in height (Laurent et al., 2017). According to Plassin et al. (2017), the soil texture conditions in Paragominas allow for intensification of land use in areas known as "chapadas" and "baixões," as their characteristics make them suitable for mechanized agriculture.

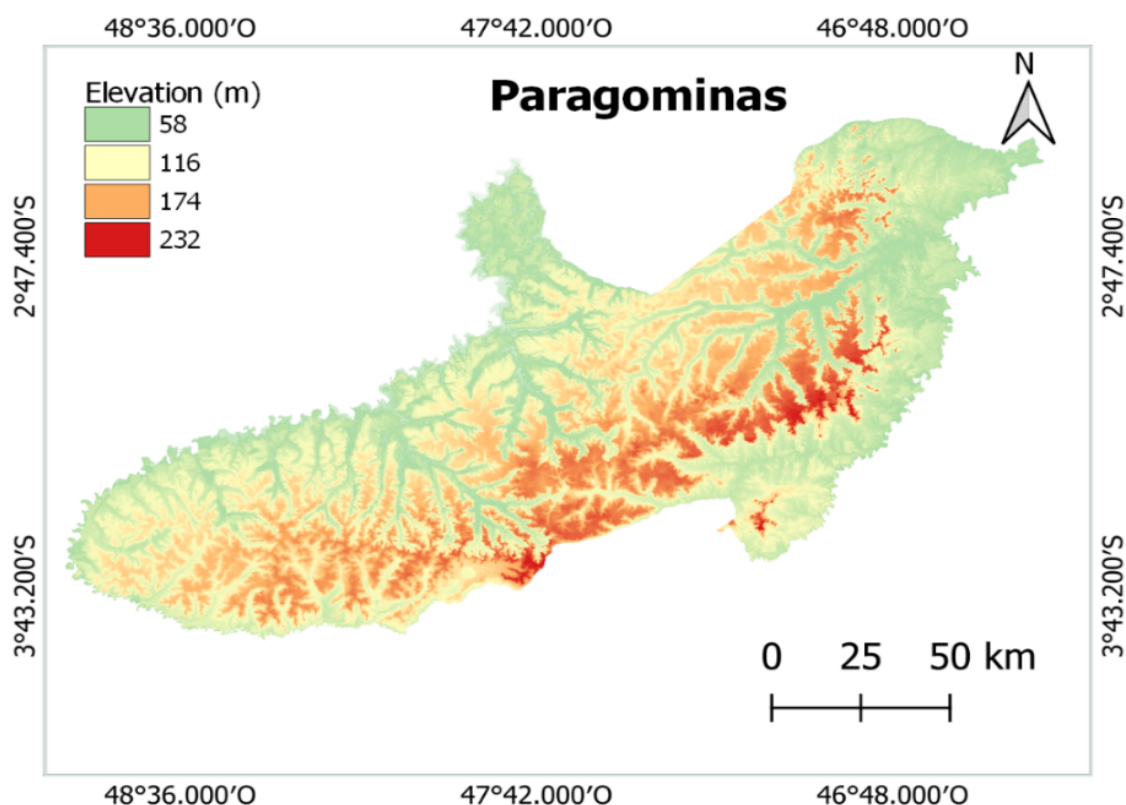


Figure 12: Elevation map of the Paragominas municipality of Brazil. Source: (Farr et al., 2007).

1.1.2.2 Socioeconomic characterization

The resident population of Paragominas was 105 550 people in 2021, representing a 7.89% increase compared to the 2010 census, with a population density of approximately 5.45 inhabitants per km² (IBGE, 2021). The Municipal Human Development Index (MHDI) improved from 0.33 in 1991 to 0.65 in 2010, indicating an overall enhancement in quality of life during this period. Additionally, the school enrollment rate for children aged 6 to 14 years is 95.9% (IBGE, 2022).

Paragominas has a diversified economy, with key sectors including cattle ranching, intensive soybean cultivation, forest management areas, mining, and family farming. In 2021, the municipal Gross Domestic Product (GDP) per capita was recorded at \$6 429 (IBGE, 2022).

1.1.2.3 Legal territorial designations

The municipality of Paragominas, founded on January 23th 1961, is predominantly composed of private properties, followed by rural settlements

and an Indigenous territory (Fig. 13). These land categories are part of the municipal legal territorial designations (Table 3).

Private property

The 1988 Federal Constitution of Brazil recognizes the right of citizens to private property (Art. 5, XXII CRFB), and further stipulates that such property must fulfill a social function. The social function requires private property to serve a social purpose. The social function is considered fulfilled when rural property addresses two aspects: a) rational and adequate use, and b) proper use of available natural resources and environmental preservation (Macedo, 2008). If the social function is not fulfilled, the property owner may face consequences outlined in the law, aimed at aligning the property's use with social interests, which could include administrative sanctions. The Rural Environmental Registry (CAR) is a mandatory public electronic registry in Brazil established by the Forest Code (Law No. 12,651/2012), where rural landowners must provide georeferenced information about the boundaries of their properties, areas of native vegetation, permanent preservation areas, and legal reserves (Soares-Filho et al., 2014). Paragominas has 1 500 private properties registered in the rural environmental registry (CAR) representing an area of 17 071 km², which represents 88.2% of the territory (SICAR, 2014).

In south-western of Paragominas municipality is located Rio Capim Fazenda (Fig. 13), which hosts sustainable forest management areas owned by Cikel Brasil Verde Madeiras Ltda. A logging company certified by the Forest Stewardship Council since 2001 (Sist and Ferreira, 2007) and the estate has permanent research plots (TmFO, 1997).

Rural settlements

Rural settlements in Brazil ("Assentamentos" in Portuguese) were a form of individual land regularization applied to land acquired, expropriated, or purchased by the federal government, which is responsible for establishing and enforcing forest resource use regulations (Santos et al., 2010). Initially, the government promoted the colonization of the Amazon, and to regularize land occupation by new settlers, the federal government created the National

Institute of Colonization and Agrarian Reform (INCRA) in 1970. As a result, 3 417 settlements were established in the Amazon between 1970 and 2013, covering approximately 8% of the total Amazonian territory in the affected states (Farias et al., 2018).

In Paragominas, there are 11 rural settlements covering an area of 1 337 km², which represents 6.9% of the municipality's total territory (Fig. 13). One of the largest and most significant settlements in Paragominas is Paragonorte, established in 1998 with an area of 321 km². It is home to 1 200 families. The settlements illustrate how agricultural intensification processes have reshaped areas initially intended for smallholder family farming. Established to promote land redistribution and rural development, these settlements have increasingly shifted toward large-scale cattle ranching. In Paragonorte and Caip, many smallholder plots were converted into extensive cattle pastures. This dynamic reflects broader patterns observed across the Amazon, where settlement areas, instead of stabilizing forest frontiers, have contributed significantly to deforestation and land-use transformation (Moura and Rocha, 2016; Osis et al., 2019).

Indigenous reserve

An indigenous reserve Alto Rio Guamá is a demarcated and protected territory designated for the permanent and exclusive use of indigenous peoples. These lands are intended for the preservation of their culture, traditions, natural resources, and social organization, as well as to ensure the physical and cultural continuity of their communities (Ortiga, 2004).

The Alto Rio Guamá Indigenous land is located in the eastern part of Paragominas, covering an area of 951 km², which represents 4.9% of the municipality's total territory.

The table 3 summarizes the legal and institutional framework in Paragominas. Law No. 4.504 of 1964, known as the Land Statute, established the basis for regulating rural land ownership and promoting agrarian reform, focusing on private properties. Law No. 8.629 of 1993 further developed the legal framework for agrarian reform, particularly regulating land settlements. Also in

1993, the Decree of October 4 formalized the homologation of the Alto Rio Guamá Indigenous Land, recognizing indigenous territorial rights. Together, these laws shaped the current land governance in Paragominas.

Table 3: Legal and institutional framework at the territory scale for the municipality of Paragominas-Brazil.

Year	Law	Description	Source
1964	Law No. 4.504 Provides for the Land Statute and Other Provisions	This law regulates the rights and obligations concerning rural real estate, for the purposes of implementing Agrarian Reform and promoting Agricultural Policy (Particular property)	http://www.car.gov.br
1993	Law No. 8.629 Provides for the regulation of the constitutional provisions related to agrarian reform, as established in Chapter III, Title VII of the Federal Constitution	This law regulates and disciplines provisions relating to agrarian reform (settlements)	http://www.ibge.gov.br
1993	Decree W/No of October 4, 1993	Homologation of the indigenous land Alto Rio Guamá in Brasilia	http://www.ibge.gov.br

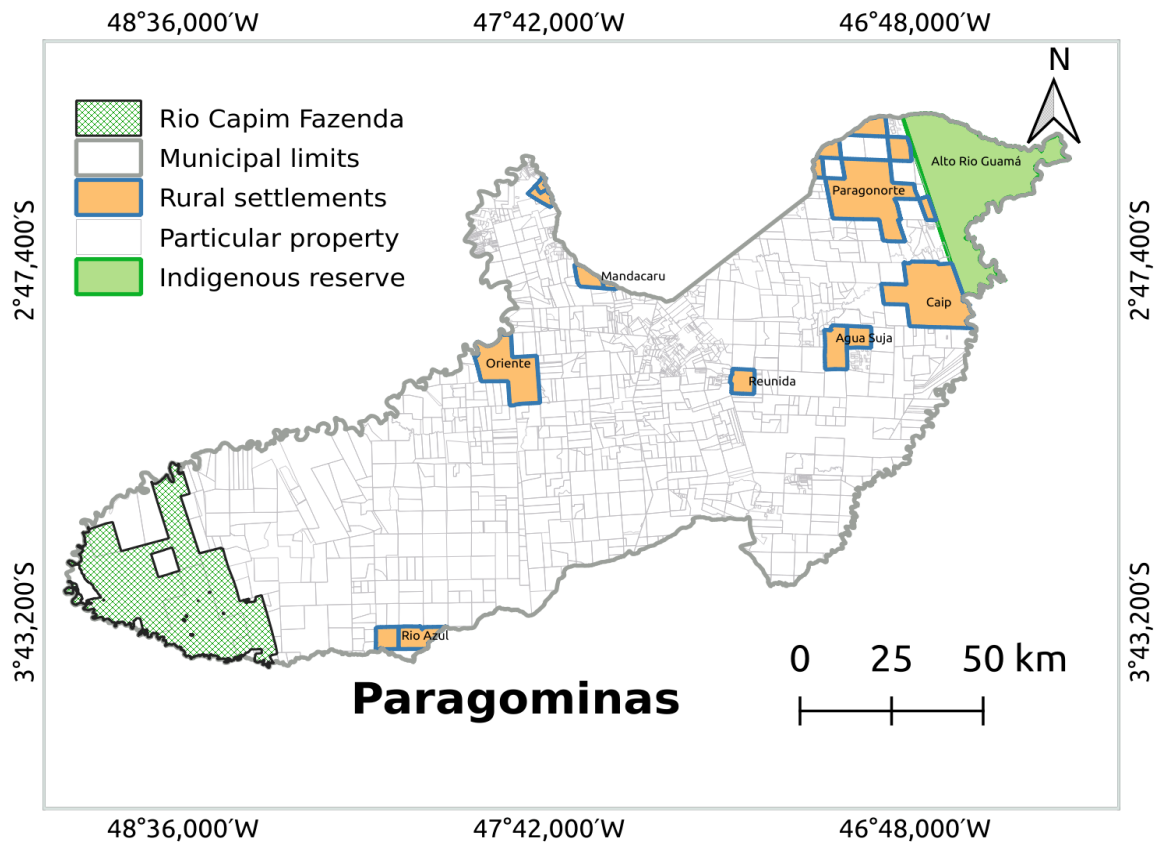


Figure 13: Legal territorial designations in the municipality of Paragominas, Brazil. Source: (IBGE, 2022).

1.1.2.4 Historical colonization processes

Indigenous peoples, such as the Temb  and Guajajara tribes, first lived in Paragominas during the pre-colonization era (Viana et al., 2012). As part of the military government's strategy to integrate the Amazon region and encourage colonization and economic growth, the colonization in the Par  state began in the 1960s (Schmink and Wood, 1992).

During the early 1960s, pioneers settled in the area, initially drawn by resource extraction opportunities, followed by private colonization companies. The name Paragominas was created by combining the names of three states Par , Goi s, and Minas Gerais which are the home states of the colonizing settlers. The first wave of colonists consisted of workers involved in infrastructure development, followed by rural migrants in search of land. At the same time, land grabbers known as grileiros began demarcating large tracts of land in anticipation of speculative sales (Bendahan et al., 2013).

As settlement advanced, land plot sizes varied significantly depending on the colonization model and regional context. In southern and southeastern Pará, some properties officially reached up to 4 500–5 000 hectares. Private colonization companies and fiscal incentives also attracted entrepreneurs from other Brazilian states, consolidating a mixed model of smallholder and large-scale colonization (Bendahan et al., 2013).

Initially, agricultural activities were based on slash-and-burn practices, with production aimed at subsistence due to poor transport infrastructure. Given these limitations, cattle ranching quickly emerged as a strategic complement. Settlers established forage crops using the ash from burned forest biomass, and employed diverse strategies to build their herds, including calf-sharing agreements and female cattle purchases (Bendahan et al., 2013). The construction of the Belém-Brasília highway (BR-010) played a crucial role in facilitating access, accelerating colonization, and accelerating deforestation.

Timber extraction preceded ranching and dominated the early economy: vast forest biomass was burned during land clearing, fueling a boom in the sawmill industry. By 1998, Paragominas had become the largest timber hub in Pará, producing approximately 2.3 million m³ of logs annually and generating a gross income of \$ 163 million about 16% of the state's timber revenue (Veríssimo, 2002).

During the 1990s and 2000s, Paragominas began integrating into the expanding soybean frontier of the southern Amazon. This agribusiness model originated in Goiás. Timber and cattle activities despite their environmental costs laid the groundwork for this transition. In parallel, the expansion of cattle ranching consolidated Paragominas as a regional cattle production center. This status was further reinforced by the establishment of a modern slaughterhouse in 2014, enabling regional and national commercialization of beef products (Laurent et al., 2017; Poccard-Chapuis, 2022).

In response to widespread deforestation, local and national actors launched the “Green Municipality” initiative in 2008. This program aimed to reverse deforestation trends and promote sustainable land use, establishing

Paragominas as a reference model for other municipalities in the Amazon (Barona et al 2010; Piketty et al., 2015).

1.1.2.5 Problematic of forest cover loss in Paragominas

In 2008, Paragominas was included in the Brazilian government's blacklist of Amazonian municipalities with the highest deforestation rates as an initiative designed to halt forest loss in areas with particularly high or recent deforestation. Despite an average deforestation rate of approximately 50%, the municipality's inclusion was unsurprising given its historical contribution to regional forest loss. Being blacklisted entails intensified governmental oversight of agricultural activities and the enforcement of strict environmental, economic, and social regulations.

Through a coordinated response involving municipal and state institutions, NGOs, and a broad coalition of stakeholders, Paragominas met the main requirements for removal from the blacklist by 2011. These included a significant reduction in deforestation rates and the implementation of the Rural Environmental Registry (CAR) across at least 80% of the municipality's properties (Osis et al., 2019; Piketty et al., 2015).

The first tangible outcome of the "Green Municipality" initiative was Paragominas' rapid removal from the blacklist. The second was the active engagement of large landowners, nearly 90% of whom adopted environmental compliance plans. The third was the considerable media visibility of the initiative, which gained national prominence, received widespread online attention, and inspired similar approaches in other blacklisted Amazonian municipalities. However, a key limitation was the minimal involvement of smallholder and family farmers, partly due to their marginal role in municipal governance and decision-making processes (Bendahan et al., 2013).

Although deforestation has significantly decreased, challenges remain, particularly in restoring secondary vegetation in abandoned or highly degraded areas (Bustamante et al., 2019; Lennox et al., 2018).

1.1.3 Cotriguaçu municipality, Brazilian Amazon

1.1.3.1 Geographical conditions

The municipality of Cotriguaçu, located in the state of Mato Grosso, central-west Brazil, covers an area of 9 423 km² (IBGE, 2023). The municipality has a dense hydrographic network, with its main rivers being the Juruena River, located in the east, and the São Miguel River, located in the west (Fig. 14). These rivers are key tributaries feeding into the Tapajós and Madeira basins. The climate is tropical, with an average annual temperature of 25°C. Between 2004 and 2020, the average annual rainfall recorded in Cotriguaçu was 2 278 mm (Silva et al., 2024).

The municipality of Cotriguaçu has a paved primary road connecting Juruena to Cotriguaçu (MT-170) with 73 km, which represents 4.88% of the total existing roads in the municipality, (Fig. 12). Next, secondary roads have a length of 1 426 km, representing 95.11% of the total number of roads in the municipality (IBGE, 2019).

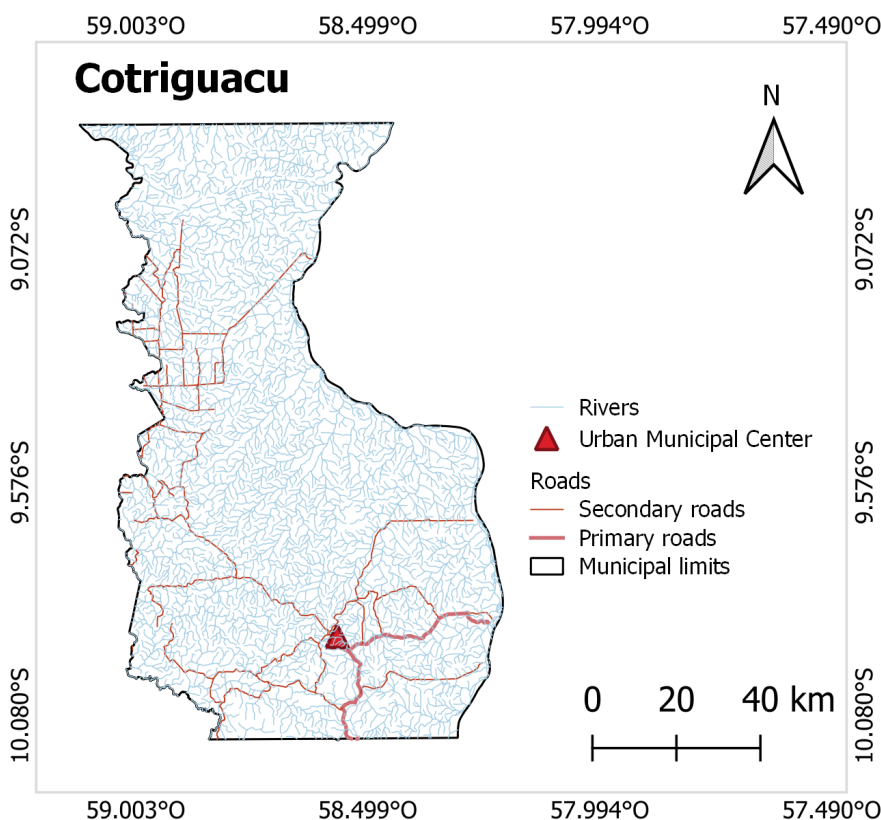


Figure 14: Map of geographical characteristics considering roads, rivers, urban municipal centers in the municipality of Cotriguaçu, Brazil.

From a geological perspective, Cotriguaçu is situated within a section of the Brazilian Shield, where the topography is moderately irregular due to frequent granite outcrops that form rocky hills ("morros"), interspersed with small low-slope plains (Fig. 10). The soils in the region are derived from granite weathering and are characterized by low fertility levels (Tavares et al., 2019). The predominant soil type is dystrophic Red-Yellow Argisol (EMBRAPA, 2011). The elevation in Cotriguaçu ranges from 117 to 466 m.a.s.l. (Farr et al., 2007). (Farr et al., 2007)

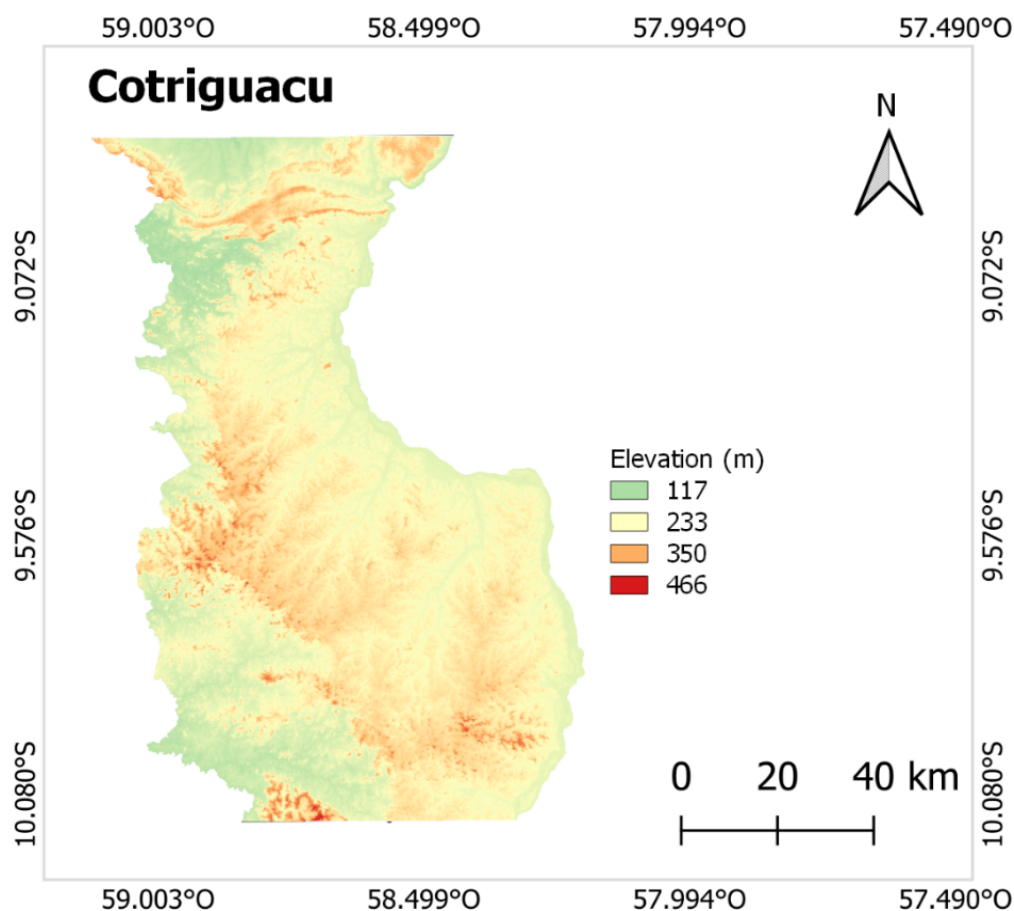


Figure 15: Elevation map of the Cotriguaçu municipality of Brazil. Source: (Farr et al., 2007).

1.1.3.2 Socioeconomic characterization

The population in Cotriguaçu was 20 717 people in 2021, representing an increase of 39.40% compared to the 2010 census, with a population density of approximately 1.21 inhabitants/km² (IBGE, 2023). The municipal human development index went from 0.38 in 1991 to 0.60 in 2010, improving their

standard of living in this period, also has 87.9% of schooling between 6 to 14 years of age of its inhabitants (IBGE, 2022). The municipality's economic activity is not very diversified, with cattle raising, forestry management and family agriculture being the most represented. In 2021, the municipal GDP per capita was \$ 2 717 (IBGE, 2022).

1.1.3.3 Legal territorial designations

The municipality of Cotriguaçu, founded on December 20, 1991, is predominantly composed of privately owned properties, followed by an Indigenous territory, a national park, and rural settlements. These land categories are part of the municipal legal and institutional framework (Table 4).

Particular Property

Particular properties in Cotriguaçu consist of 1 003 registered properties, covering a total area of 5 252 km². These properties are recorded in the Cadastro Ambiental Rural (CAR), representing 55.4% of the municipality's total area.

Rural Settlements

In Cotriguaçu, two Settlement Projects have been implemented (Fig. 11): Nova Cotriguaçu, established in 1993, is the second-largest settlement in the state, covering 869.58 km² and divided into 1 502 parcels. It borders the Escondido Indigenous Territory and the Juruena National Park. By 2014, it housed 1 282 settled families (Piroux and Jahel, 2022).

Juruena, established in 1997, covers 307.93 km² along the margins of the Juruena River. It consists of 524 officially recognized parcels and 207 parcels designated as part of a collective legal reserve, with approximately 560 settled families (Município de Cotriguaçu, 2023).

Indigenous Reserve

The Escondido Indigenous Reserve, officially recognized in 1998, is part of the protected areas within the municipality of Cotriguaçu. Covering an area of 1 664 km², it represents 17.56% of the municipality's total area. It is inhabited

by the Rikbaktsa people, whose main village is located in the southwestern part of the reserve (Brasil, 1998).

National Parks

The Juruena National Park, established on June 5, 2006, is located in the northern part of Cotriguaçu. It covers an area of 1 382 km², representing 14.59% of the municipality's territory. This park was created with the objective of ensuring the strict protection of biological diversity and forest resources in the Juruena-Teles Pires region (Brasil, 2006).

Table 4: Legal territorial designations at the territory scale for the municipality of Cotriguaçu -Brazil.

Year	Law	Description	Source
1964	Law No. 4.504 Provides for the Land Statute and other provisions.	This law regulates the rights and obligations concerning rural real estate, for the purposes of implementing Agrarian Reform and promoting Agricultural Policy (Particular property)	http://www.car.gov.br
1993	Law No. 8.629 Provides for the regulation of the constitutional provisions related to agrarian reform, as set forth in Chapter III, Title VII of the Federal Constitution.	This law regulates and disciplines provisions relating to agrarian reform (settlements)	http://www.ibge.gov.br
1997	Decree Without/No of 08.09.1997	Homologation of the indigenous land Escondido	
2006	Decree Without/No of 05.06.2006	Creates the Juruena National Park	http://www.ibge.gov.br

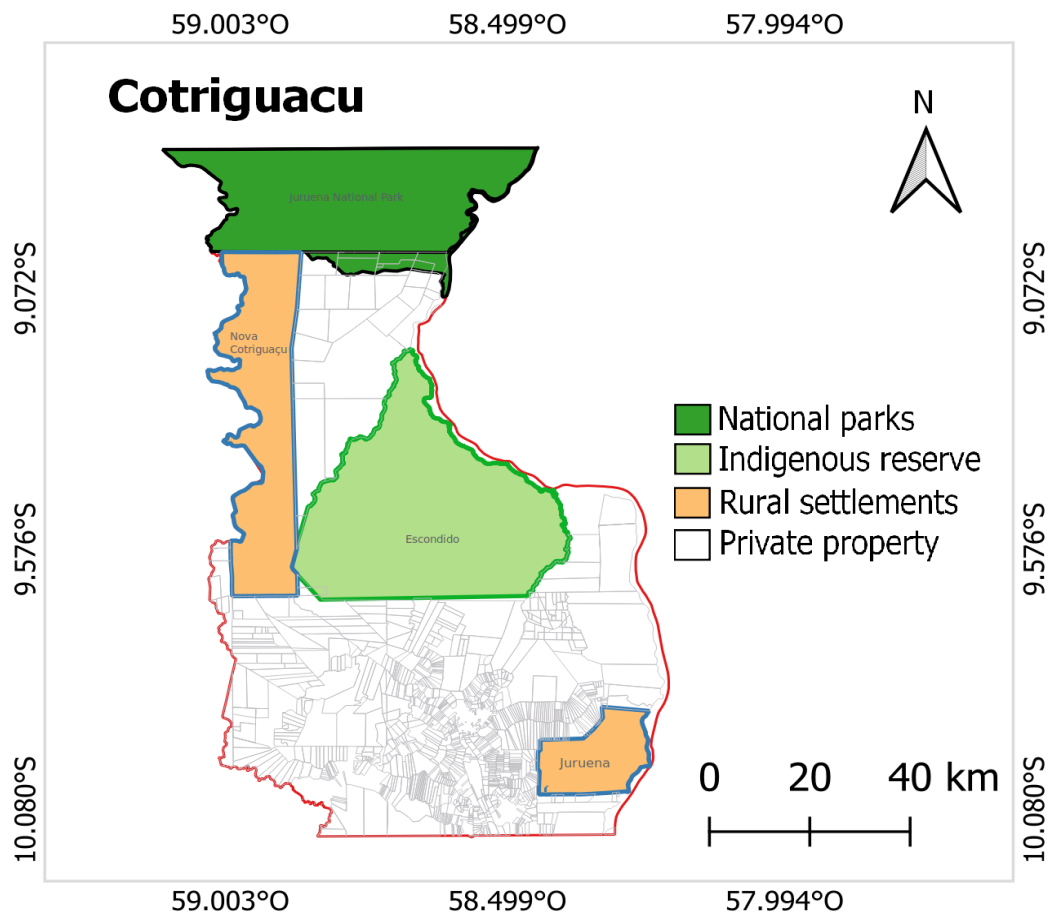


Figure 16: Legal territorial designations in the municipality of Cotriguaçu, Brazil.
Source (IBGE, 2023).

1.1.3.4 Historical colonization processes

In the Pre-colonization era, the Rikbaktsa indigenous peoples once occupied what is now Cotriguaçu (Sills et al., 2014). As part of its efforts to develop the Amazon region, the Brazilian government started colonizing Mato Grosso in the late 1970s. Private colonization businesses were the main driving force behind the colonization. Smallholders from Rio Grande do Sul moved north to Mato Grosso in order to expand their farming territory (Jepson, 2006).

Colonization in Cotriguaçu began in 1984 with the arrival of the first land owners. This municipality had a large part of its territory unoccupied which made possible the implementation of several projects of human settlements attracting a large number of families from Mato Grosso do Sul and Rondônia.

Cotriguaçu was officially founded on December 20, 1991, when it was emancipated from the municipality of Juruena (IBGE - Instituto Brasileiro de

Geografia e Estatística). In the initial colonization period economic activities focused on logging and agriculture (Guerra, 2016). The region's dense forests attracted logging companies, while small-scale farmers engaged in subsistence agriculture and cattle ranching (Asner et al., 2009).

1.1.3.5 Problematic of forest cover loss in Cotriguaçu

In 2008, similar to Paragominas, the municipality of Cotriguaçu was listed among the municipalities with the highest deforestation rates in the Amazon. Since then, various projects implemented by the municipal government, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) program, NGOs, and local stakeholders have contributed to significant progress in counteracting deforestation and implementing the Rural Environmental Registry (CAR) at the municipal level (ICV, 2013). In 2018, Cotriguaçu joined the Produce, Conserve, and Include (PCI) initiative of the state of Mato Grosso, a low-carbon agricultural development agreement aimed at combating climate change (ICV, 2023).

In recent years, there have been efforts to promote more sustainable land use practices in Cotriguaçu (Gil et al., 2015). The municipality has been part of pilot projects for REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and other conservation initiatives (Sills et al., 2014). Cotriguaçu continues to face challenges balancing economic development with environmental conservation. It remains an important area for studying the dynamics of new frontier expansion in the Amazon (Schielein and Börner, 2018) and social policies to stabilize forest agriculture frontiers (van Vliet et al., 2013).

1.2 Available indicators of forest cover and climate change at the study site level

1.2.1 Data

1.2.1.1 International data bases

MAPBIOMAS data

The MapBiomass database (Collection 7.0) contains time series from 1985–2021 of 12 classes: forest formation, savanna formation, forest plantation, wetland, grasslands, pasture, urban area, mining, river, soybean, other temporary crops and other perennial crops. The MapBiomass database is based on Landsat

imagery (MapBiomas, 2024) available at <https://brasil.mapbiomas.org>. The MapBiomas dataset is available in raster format (GeoTIFF), with a spatial resolution of 30 m, a geographic coordinate system and Datum WGS-84. This product, although very useful, does not provide detailed information on the level of forest degradation. Source: <https://amazonia.mapbiomas.org/>

The MAPBIOMAS Amazonia program is a multi-institutional initiative involving universities, NGOs, and technological institutes, designed to map land cover and land use changes across the Amazon biome. The Biomass Amazonia platform provides annual land cover and land use mapping for the Amazon at a spatial resolution of 30-meters. These maps include 19 land use classes and statistical values, available for the Amazonian regions of nine countries: Brazil, French Guiana, Suriname, Guyana, Venezuela, Colombia, Ecuador, Peru, and Bolivia.

TMF data (Tropical Moist Forest data)

The Tropical Moist Forest (TMF) program of the Joint Research Centre (JRC) of the European Commission provides global-scale information on changes in tropical moist forest cover. The dataset included the period from 1990 to 2021, offering annual temporal resolution. This dataset includes deforestation, degradation, and regeneration processes. The maps are generated at a 30-meter resolution using time series of Landsat imagery.

The 'Annual change collection' of the Tropical Moist Forest (TMF) dataset is based on a 32-year Landsat time series (1990-2021) (Vancutsem et al., 2021). Each disturbance, whether deforestation or degradation, has its own distinct timing and intensity. Deforestation implies a change in land use 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 observed over the full observation period.

One of the key strengths of the TMF dataset is its capacity to separately detect and monitor forest degradation processes, which have traditionally been more

difficult to assess compared to deforestation. Degraded forests are critical to consider because they maintain some ecological functions but are often more vulnerable to future deforestation. The dataset also tracks the regeneration of previously disturbed areas, capturing the recovery of forest cover after abandonment or natural recovery processes. By offering detailed annual change information at high spatial resolution, the TMF dataset enables robust spatial and temporal analyses of tropical forest dynamics across different biomes and regions. Source: <https://forobs.jrc.ec.europa.eu/TMF//>

While MAPBIOMAS relies on Landsat imagery and annual classifications of land use and cover transitions, the TMF dataset uses a change-detection algorithm based on dense time-series analysis to distinguish between deforestation and degradation. A key feature of the TMF method is its reliance on the duration of canopy disturbance: short-term disturbances (less than 2.5 years) are classified as degradation, whereas permanent losses or disturbances exceeding 3 years are considered deforestation. This temporal criterion improves the detection of selective logging and fire-induced canopy openings, which are often underrepresented in annual classification models.

GLAD-Fire data (Global Land Analysis and Discovery)

The GLAD-Fire (Global Forest Loss due to Fire) program of the University of Maryland has produced the first global satellite-based map at 30-meter resolution depicting annual forest loss due to fires (Tyukavina et al., 2022). This dataset is available for the 2001–2021 period. Annual forest loss due to fires is analyzed only in tree cover areas mapped by the Global Forest Watch monitoring system (Hansen et al., 2013). The dataset specifically measures fires affecting primary forests, while low-intensity fires and understory fires that do not result in substantial canopy loss at a 30-meter pixel scale are excluded from the analysis. Source: https://glad.umd.edu/dataset/Fire_GFL

MODIS-Fire data

The MODIS-Fire program provides active fire and burned area products that offer unique information for understanding the chronology, spatial distribution, and characteristics of fires. The MODIS Standard Fire Products (MODIS Active

Fire and MODIS Burned Area) make a significant contribution to NASA's Land Use and Land Cover program and the Global Observation of Forest Cover (GOFC) international project. The dataset used corresponds to the MODIS Burned Area product.

The MODIS burned area mapping algorithm detects these spectral, temporal, and structural changes, determining the approximate burn date at a spatial resolution of 500 m. It does so by identifying rapid changes in the daily surface reflectance time series. The algorithm maps the spatial extent of recent fires, but does not capture fires that occurred in previous seasons or years. MODIS-Fire source: <https://modis-fire.umd.edu/ba.html>

Precipitation data

Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) is a publicly available precipitation database since 2014 created by the U.S. Geological Survey (USGS) and the University of California. We downloaded CHIRPS using the collection: UCSB-CHG/CHIRPS/PENTAD. CHIRPS incorporates station data. The spatial resolution of this product was 5-kilometers (Funk et al., 2015).

1.2.1.2 National data bases

Brazil

The PRODES program of the National Institute for Space Research (INPE) has been generating deforestation data for primary forests in the Legal Amazon since 1988. The available data include annual deforestation rates and primary forest cover, which can be accessed through the TerraBrasilis platform, source: <https://terrabrasilis.dpi.inpe.br/>. Through the PRODES program, INPE produces maps of deforested areas across Brazil's Legal Amazon using Landsat imagery with a 30-meter spatial resolution. Deforestation data are released annually in December, covering the period from August of the previous year to July of the current year. The methodology is limited by cloud cover presence and the length of the dry season, which affects the analysis. Additionally, INPE does not provide annual statistics on forest degradation in the Brazilian Amazon (INPE, 2019a).

Source (1) <http://www.dpi.inpe.br/prodesdigital/prodesmunicipal.php>

Source (2) : <http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/amazon/increments>

Colombia

The IDEAM-SMByC program is Colombia's official system for deforestation monitoring and assessment, managed by the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM). It focuses exclusively on deforestation quantification at national and regional scales, using medium-resolution 30-meter satellite imagery and producing data at a 1:100 000 scale (IDEAM, 2017).

Official deforestation data were initially published for the periods 2000–2005, 2005–2010, and 2010–2012, and since 2013, updates have been released annually. For the Amazon region, IDEAM collaborates with the Amazonian Scientific Research Institute (SINCHI), which is responsible for conducting, coordinating, and disseminating scientific studies on the Amazon region.

Source : <http://www.ideam.gov.co/web/ecosistemas/alertas-tempranas-por-deforestacion>

1.2.1.3 Comparison of the data bases and choice

The main difference between the INPE-PRODES and JRC-TMF datasets lies in how they classify burned areas. PRODES does not consider burned areas as deforested unless there is clear evidence of a land-use change, such as conversion to pasture or cropland. Consequently, these areas are only classified as deforested once agricultural activity is observed. In contrast, the JRC-TMF dataset often classifies severely burned areas as deforested when certain conditions are met, based on Landsat time series analysis. First, if no tree canopy recovery is detected in the years following a fire event, the area is classified as deforested rather than degraded. Second, if a pixel remains consistently non-forested for more three years, the change is considered permanent deforestation. Third, repeated or particularly severe fire events (in terms of intensity and spatial extent) increase the likelihood of classification as deforestation. This methodological distinction explains some discrepancies

between the datasets, particularly during extreme drought years such as 2016, when large-scale wildfires affected the Amazon (Beuchle et al., 2021).

PRODES, for instance, uses a minimum mapping unit of 6.25 hectares and focuses exclusively on clear-cut deforestation, without identifying degradation or regrowth. JRC-TMF, on the other hand, by distinguishing between deforestation, degradation, and regeneration, provide a more nuanced picture of forest dynamics. Temporal coverage also differs: PRODES reports deforestation annually based on a “deforestation year” from August to July, whereas JRC-TMF provides calendar-year annual data from 1990 to 2021. Furthermore, while PRODES combines automated classification with manual expert review, JRC-TMF is based on a fully automated, dense time-series analysis. Lastly, their geographic scope differs: JRC-TMF is a global product focused on tropical moist forests, whereas PRODES is specific to the Brazilian Amazon biome.

For this study, we selected the JRC-TMF dataset because it consistently integrates deforestation, forest degradation, and regeneration processes across all tropical moist forests from 1990 to 2021. TMF is particularly effective at capturing early degradation signals, offering detailed insights into forest dynamics. In contrast, MapBiomas provides a broader land-use perspective, which complements the TMF's focus on canopy disturbance. The combined use of both datasets thus enhances our ability to analyze forest cover change trajectories in diverse tropical landscapes. To assess fire dynamics, we also incorporated the GLAD-Fire and MODIS-Fire datasets, chosen for their scientifically validated methodologies, global coverage, and open accessibility. These sources enable reproducible and comparable analyses across the three subnational jurisdictions examined in this study.

1.2.2 Methods

Spatiotemporal land use data set from TMF and MapBiomass integration

The assessment of spatiotemporal dynamics in land use in the three study sites was based on the integration Land use maps provided by the MapBiomass project (MapBiomass, 2024) and the Tropical Moist Forest (TMF) product from the European Commission's Joint Research Centre (EC-JRC). To facilitate temporal analysis, we constructed a new time series combining both datasets for the period 1991 to 2021, but selected only 7 dates (1991, 1996, 2001, 2006, 2011, 2016, and 2021) to visualize our results.

The methodological sequence was designed in three steps to combine annual change product and land use data between 1991–2021. We reclassified MapBiomass' yearly land use time series first to split the most relevant Amazonian forest process land cover classes. Meanwhile, we reclassified TMF-JRC time series to retain only the yearly forest-related classes: undisturbed forest, degraded forest and regrowth. In step two, the two reclassified datasets were combined to generate a harmonized classification that combines land use with forest classes. 12 initial categories such as undisturbed forest, degraded forest, regrowth, pasture, soybean, and mosaic of uses were present in this classification. All the other TMF labels were replaced by their corresponding MapBiomass classes to ensure consistency and landscape heterogeneity. For the final step, we selected six leading land use types that are primary avenues of forest transformation: undisturbed tropical forest, degraded tropical forest, regrowth, pasture, mosaic of uses, and soybean (Fig. 17).

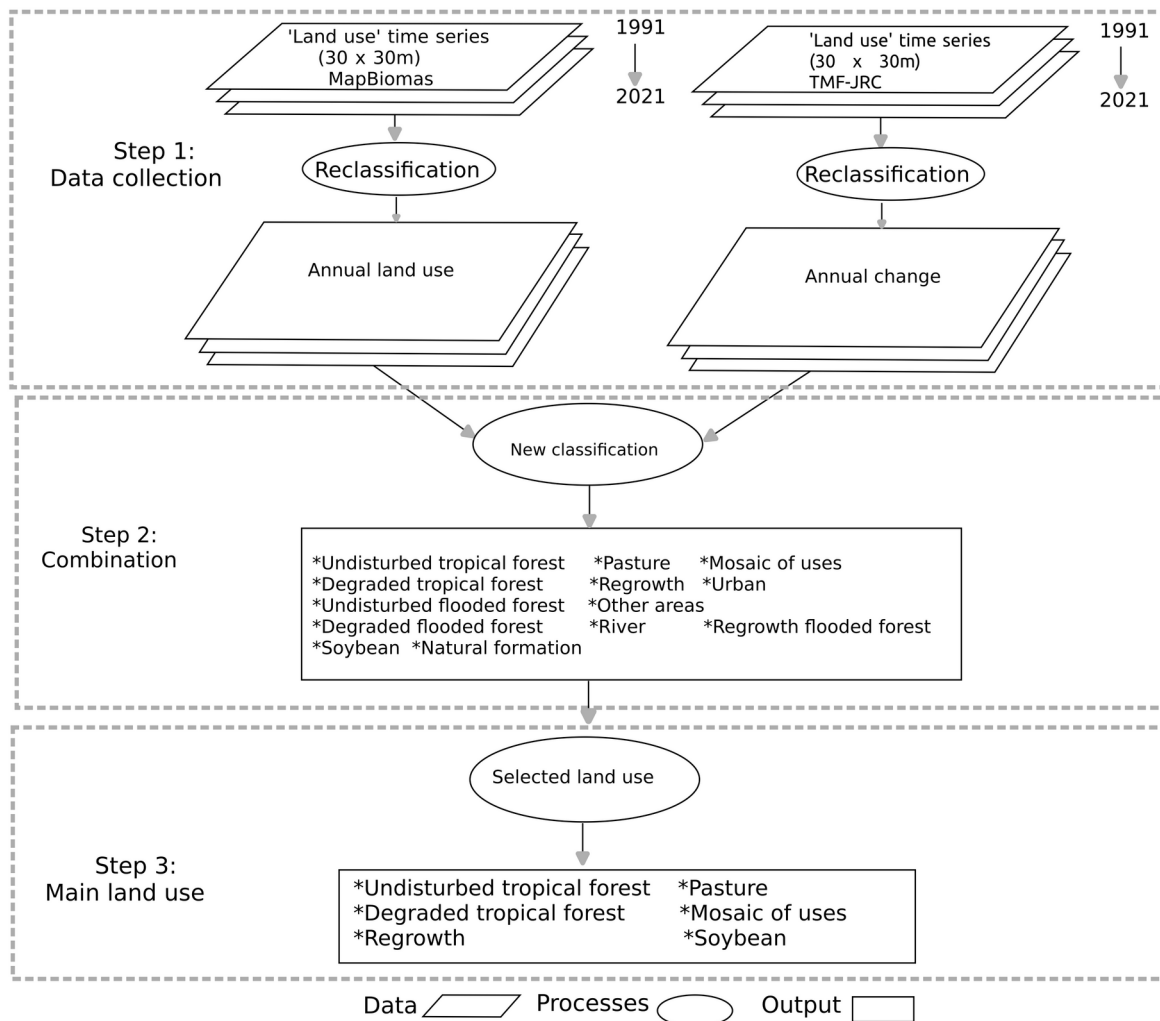


Figure 17: Reclassified land use data based on MapBiomass 7 and JRC-TMF Integration.

Temporal analysis of transitions with Sankey Diagrams

Land Use (LU) transitions were also investigated in greater detail through the use of Sankey diagrams, which are graphical representations from transition matrices. Transition matrices quantitatively assess how land use classes alter over time by expressing the amount of area shifting between classes from one time step to the next. Sankey diagrams show these transitions as flows (or "streams") between vertically stacked bars, where each bar is the aggregate area of LU categories for a year (1991, 2005, and 2021). The flows are sized by the area that changed from one LU category to another, and the height of each bar is the relative proportion of each LU type in the study areas. Transition flow between bars indicates areas undergoing LU change or stability. The thickness

of every flow is inversely related to the total area of the given transition or constant LU class. Sankey diagrams were computed with 'crosstab' function of the 'terra' package (Hijmans, 2020) in R 4.1.2.

Monitoring land use and fire dynamics

We assessed land use and fire dynamics from 2001 to 2021 by integrating land cover data from MapBiomass Collection 7 and JRC-TMF with two complementary fire datasets: GLAD-Fire was overlaid with the combined land cover dataset to quantify burned areas by different forest classes. In parallel, MODIS-Fire (500 m resolution) was used to assess fire occurrence across six broader land use categories, providing a coarser but more consistent temporal coverage. This dual approach allowed for a more robust spatial and temporal characterization of fire dynamics in relation to land use type.

Spatial analysis of Precipitation with CHIRPS dataset

To analyze average precipitation and its standard deviation, we used CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), which provides gridded rainfall data at 5 km resolution. We extracted annual precipitation values for each pixel from 2003 to 2021 across the study sites. For each pixel, the average precipitation and standard deviation were calculated over the full period to assess both central tendency and inter-annual variability. This was performed using raster calculations in R using the terra package.

1.2.3 Forest cover change and environmental indicators

1.2.3.1 Deforestation

For deforestation analysis, we used the four available databases: IDEAM

and TMF for the Colombian site, and PRODES, MapBiomass and TMF for the Brazilian sites.

In Guaviare, the total deforested area between 1990 and 2021 was 4 269 km² according to JRC. The deforestation indicator for the Guaviare department exhibits three main periods. The first phase, from 1990 to 2000, shows continuous increase, from 8.57 km² in 1990 to 189.60 km² in 2000 (Fig. 13A).

The second phase, between 2001 and 2016, represents a period of stabilization with an average annual rate of 147.27 km². The third phase, characterized by an increase, occurred in 2017 and 2018, reaching peak values of 315.52 km² and 328.21 km², respectively. The temporal distribution of deforestation across the analysis period is consistent across the two information sources, IDEAM and JRC-TMF (Fig. 18).

In Paragominas, the total deforested area between 1990 and 2021 was 3 555 km² according to JRC. The temporal dynamics of deforestation show two distinct phases. The first phase, from 1990 to 2004, exhibits continuous growth, from 4.79 km² in 1990 to 204.39 km² in 2004 (Fig. 13B). The second phase, from 2005 to 2021, shows a decline, with an average annual rate of 114.04 km². However, a comparison between JRC and PRODES data for the period 2013 to 2016 reveals discrepancies: while JRC identifies higher deforestation values, PRODES reports significantly lower rates for the same years. This divergence can be attributed to methodological differences, including JRC's ability to detect smaller-scale or more diffuse clearing events that may not be consistently captured by PRODES, which focuses on clear-cut deforestation of primary forests.

In Cotriguaçu, the total deforested area between 1990 and 2021 was 2 404.22 km². The temporal dynamics of deforestation reveal two distinct phases. The first phase, from 1990 to 2004, shows continuous growth, from 10.23 km² in 1990 to 312.74 km² in 2004 (Fig. 18C). The second phase, from 2005 to 2021, reflects a decline, with an average annual value of 74.92 km². Regarding forest degradation, two phases are observed. The first phase, from 1990 to 2004, shows growth from 9.56 km² to 51.23 km². The second phase, from 2005 to

2021, is marked by stabilization, with an annual average of 27.07 km².

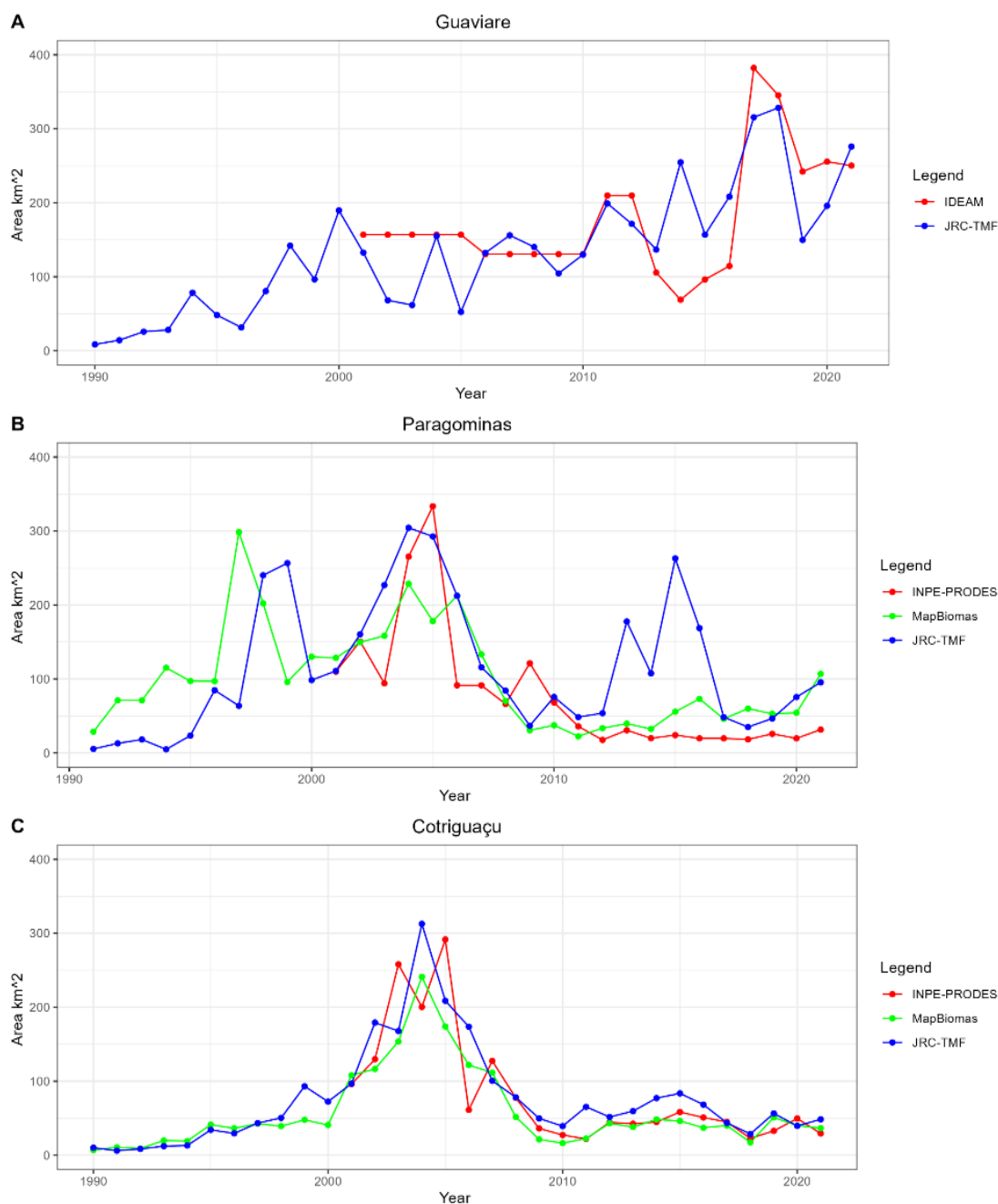


Figure 18: Annual deforestation area of three subnational jurisdictions in the Amazon: Guaviare, Paragominas, and Cotriguaçu, with national (IDEAM, INPE-PRODES) and international (JRC-TMF, MapBiomas) data sources.

The spatial pattern of deforestation in Guaviare reveals a concentration of forest loss in the northern and northwestern parts of the department, particularly around the municipalities of San José del Guaviare and Calamar. The central region displays a diffuse spread of deforested patches, evolving from early clearing in central areas to more recent activity in peripheral zones.

The southern municipalities, such as Miraflores and El Retorno, exhibit lower but old deforestation signals (Fig. 19).

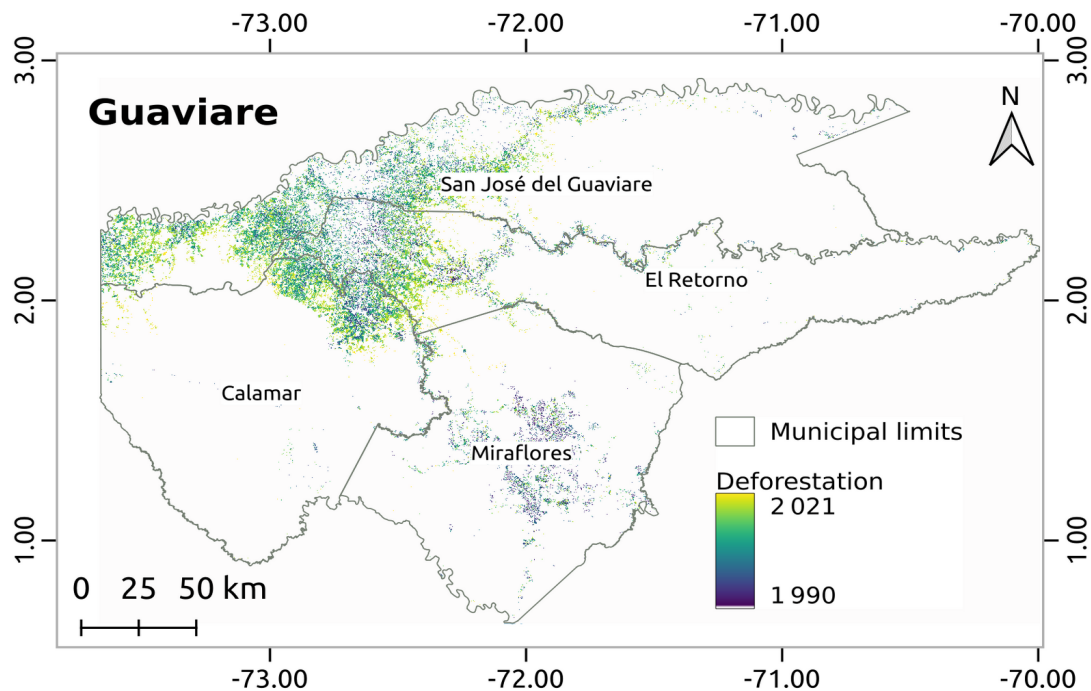


Figure 19: Spatio-temporal pattern of deforestation in the department of Guaviare (1990–2021). Source: JRC-TMF.

The spatial pattern of deforestation in Paragominas reveals a widespread distribution of forest loss across the municipality, with early deforestation events (1990s–2000s) concentrated in the central and southern regions. These areas are characterized by large, contiguous patches. This pattern reflects a shift from extensive clearings to more fragmented and opportunistic deforestation, possibly associated with land use intensification, pasture expansion, and agricultural diversification (Fig. 20).

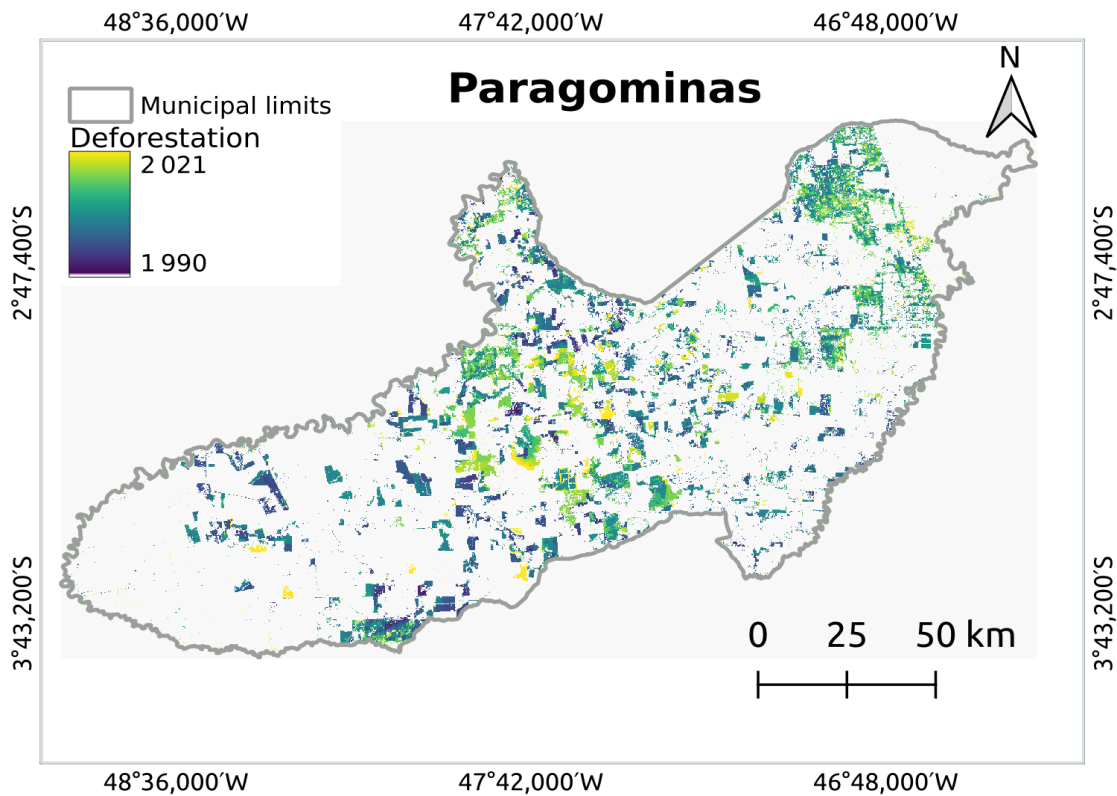


Figure 20: Spatio-temporal distribution of deforestation in Paragominas, Brazil (1990–2021). Source: JRC-TMF.

The spatial distribution of deforestation in Cotriguaçu shows a clear concentration in the southern and southwestern of the municipality, where older deforestation (1990s–2000s) appears in dense, contiguous patches. In the northern part of the municipality, deforestation is sparser, with some isolated recent events (Fig. 21).

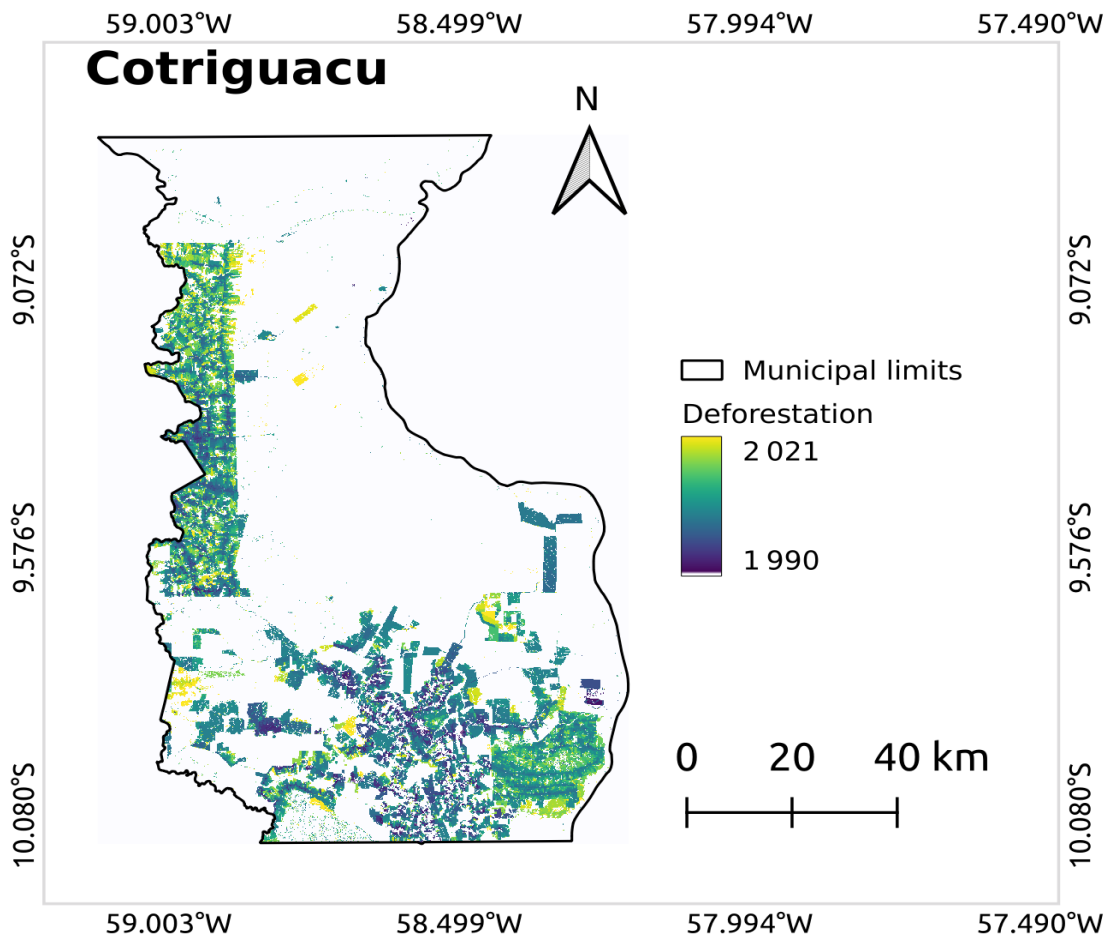


Figure 21: Spatio-temporal distribution of deforestation in Cotriguaçu, Brazil (1990–2021). Source: JRC-TMF.

1.2.2.2 Forest degradation

To study the dynamics of forest degradation, we used TMF data, which is the only product offering a mapping of this land cover class.

In Guaviare, we observe three stages of forest degradation. An acceleration phase that reaches a maximum value of 256 km² occurs between 1996 and 2000. Following that, a decline occurred between 2006 and 2015, when a value of 53 km² was recorded. Following that, there was a notable increase from 2017 to 2018, when it reached a value of 274 km², followed by a subsequent decrease, which reached 88 km² in 2021 (Fig. 17A). Meanwhile, the process of forest degradation presents four peaks during the 1990–2021 period. The first peak occurred in 1993, with an area of 137.54 km², the second in 1999, with 233.39 km², the third in 2006, with 370.61 km² and the largest in 2016, with an

area of 743.12 km². These degradation peaks correspond to dry periods in the Amazon region (1992/1993, 1998/1999, 2005/2006, and 2015/2016). Three data sources (INPE-PRODES, MapBiomas, and JRC-TMF) show similar patterns, with the exception of JRC-TMF in 2015.

Three highest values in forest degradation were observed in Paragominas over the study period (Fig. 17B). Years 1999, 2006, and 2016 had the largest values, with corresponding areas of 233 km², 370 km², and 743 km².

Cotriguaçu exhibits two phases of degradation. The first, between 1998 and 2008, had an average value of 40 km², followed by a reduction between 2009 and 2021, with an average value of 22 km²(Fig. 22C).

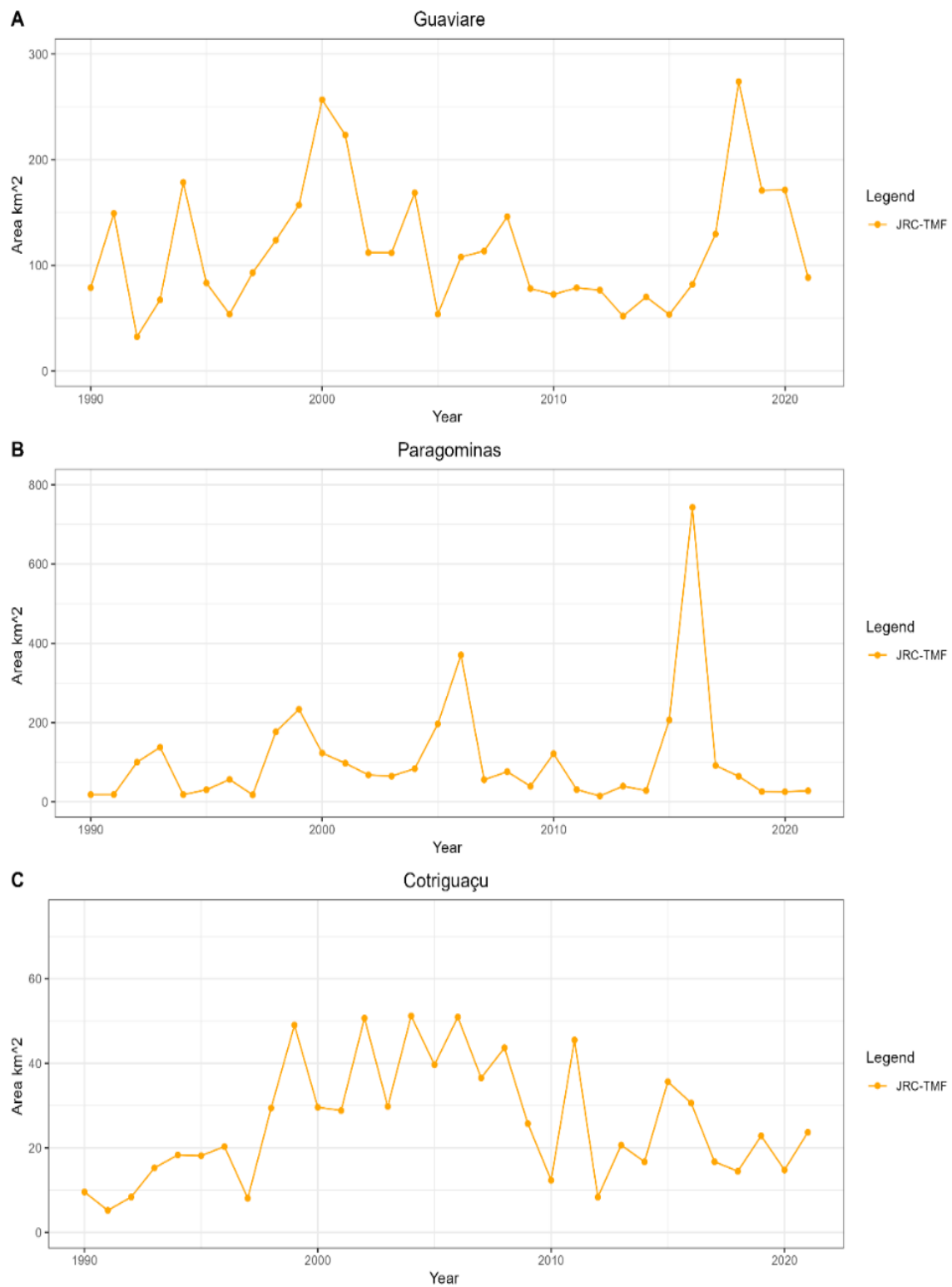


Figure 22: Annual area of degraded forest in three subnational jurisdictions of the Amazon: Guaviare, Paragominas, and Cotriguaçu. Data source: JRC-TMF.

The spatial pattern of forest degradation in Guaviare reveals a clear concentration in the northern and central-western regions of the department, particularly around San José del Guaviare and Calamar. Significant degradation is also observed near Miraflores. The distribution follows a pattern associated with colonization zones (Fig.23).

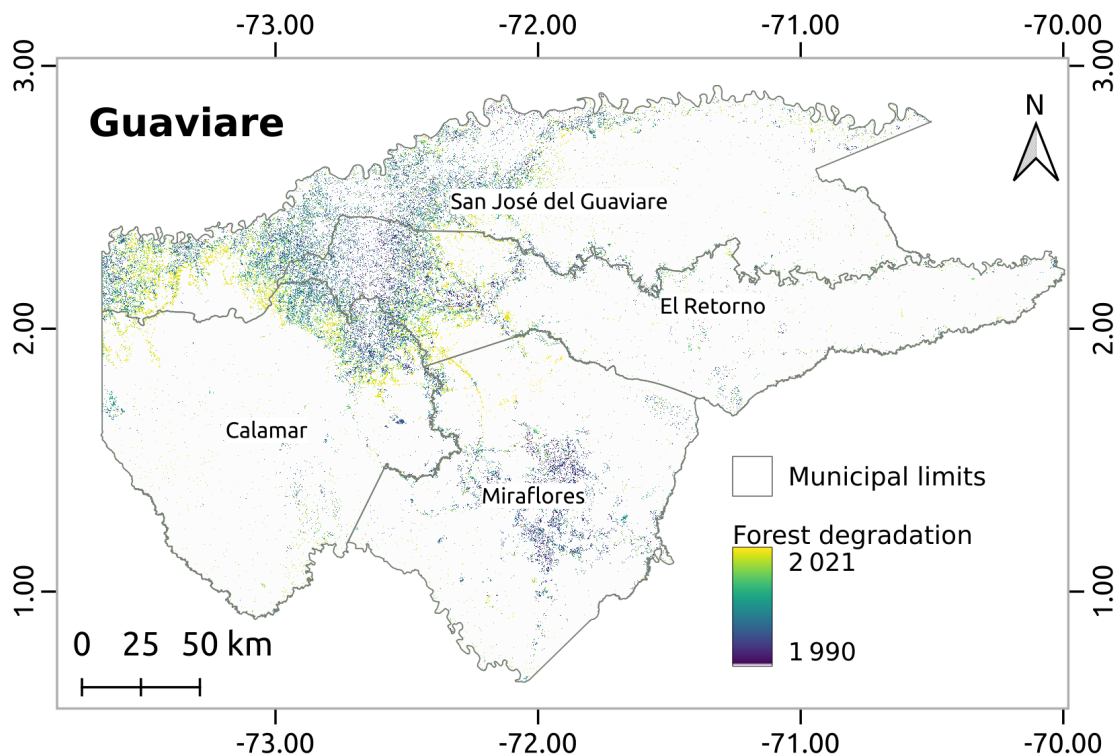


Figure 23: Spatial distribution of forest degradation in the department of Guaviare, Colombia, from 1990 to 2021. Data source: JRC-TMF.

The spatial pattern of forest degradation in Paragominas is widely dispersed across the municipality, with notable concentrations in the eastern and southeastern regions. Recent degradation events are scattered across previously degraded areas. The spatial distribution reflects the interaction between fire, and selective logging activities (Fig. 24).

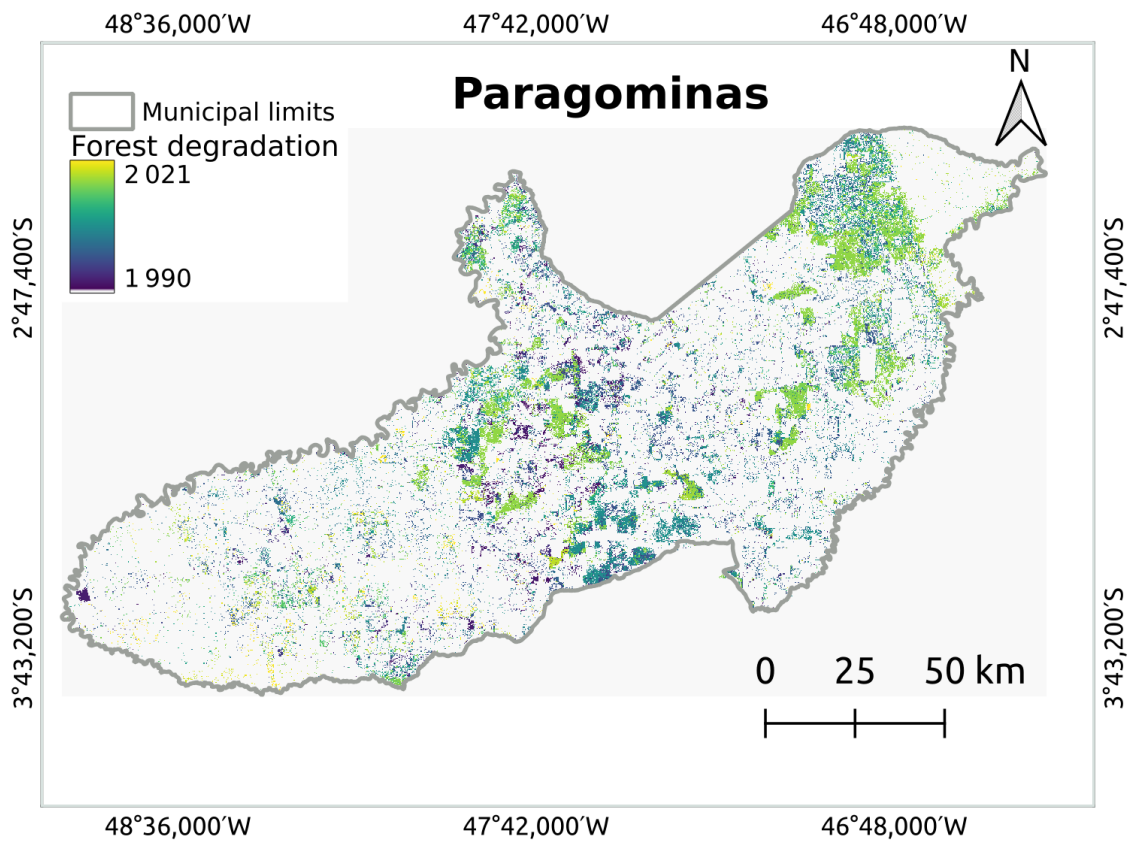


Figure 24. Spatio-temporal distribution of forest degradation in Paragominas, Brazil from 1990 to 2021. Data source: JRC-TMF.

Forest degradation in Cotriguaçu is more concentrated in the southern and southwestern portions of the municipality, overlapping with areas previously affected by deforestation. The northern and central zones exhibit a lower density of degradation events, though isolated patches are still evident. Recent degradation appears dispersed but generally follows the same pattern of previously disturbed regions (Fig. 25).

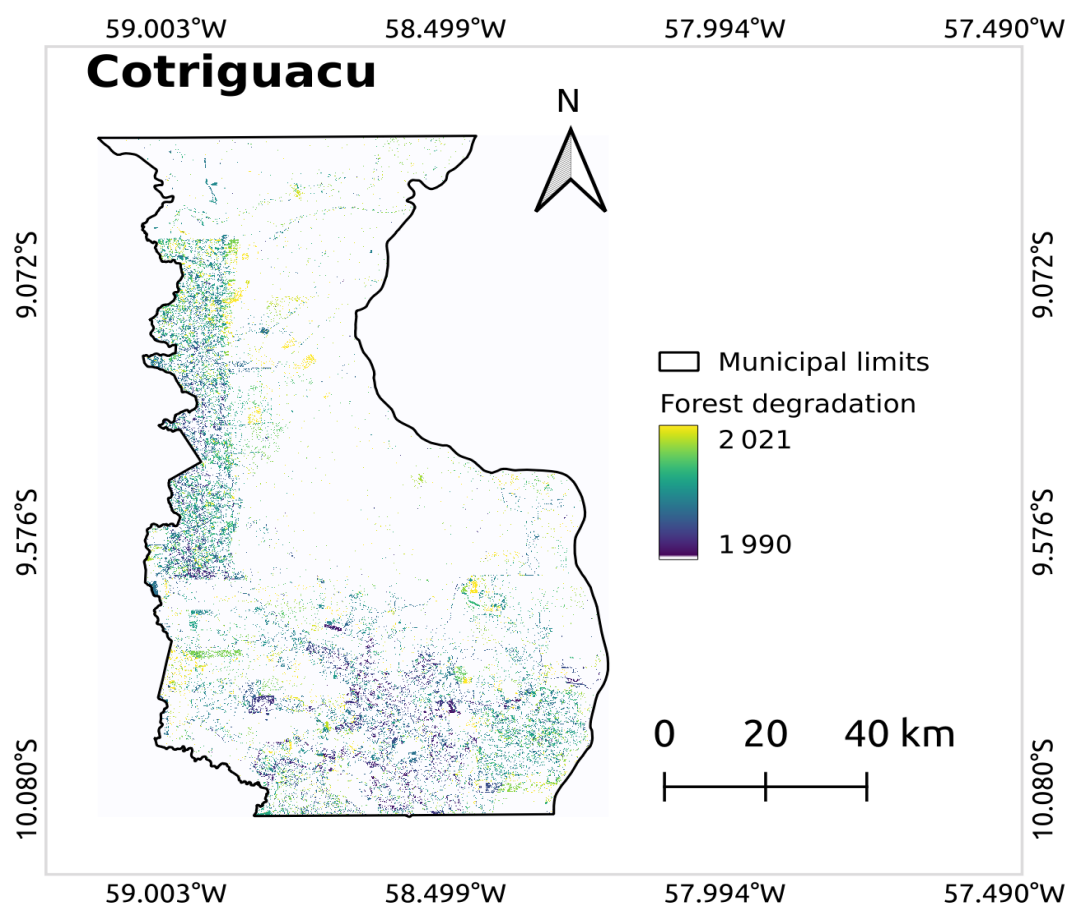


Figure 25: Spatio-temporal distribution of forest degradation in Cotriguaçu, Brazil from 1990 to 2021. Data source: JRC-TMF.

1.2.3.3 Secondary forest

As for the forest degradation analysis, we used TMF data to study the dynamics of forest regeneration which is the only product offering a mapping of this land cover class.

In Guaviare, the total area of secondary forest was 554.46 km² in the 1990-2019 period (Fig. 21A). This is the sum of all the annual secondary forest areas. This does not necessarily mean that this value will be correct in 2021, as some of the secondary forests are being deforested once more. The Forest regeneration in Guaviare is found in two phases. The first stage is characterized by low yearly amounts, below 18 km². The second stage, which stretches from 2001 to 2019, shows the growth of secondary forests with a mean of 26.53 km² yearly.

In Paragominas, 571.98 km² of secondary forest for the period 1990-2019 (Fig. 21B) representing the accumulation of annual regeneration. Two stages of forest regrowth occurred in the region. The first one between 1991 and 2015 was accompanied by low rates of annual growth of less than 16 km² per year. On the other hand, the second period began in 2016, with its peak increase in secondary forest area at 114.52 km² in 2018 and 187.35 km² in 2019.

In Cotriguaçu, the total area of secondary forest was very limited from 1990 to 2009, totaling only 11 km². There was a discrete increase from 2010 to 2019, with an average of 9 km² between this period. As with Paragominas, two phases of regeneration were identified. The first (1991-2009) showed low regeneration rates, always less than 4 km² annually. The second phase showed a gradual increase with the highest values in 2012 and 2019, corresponding to 23.14 km² and 18.84 km², respectively.

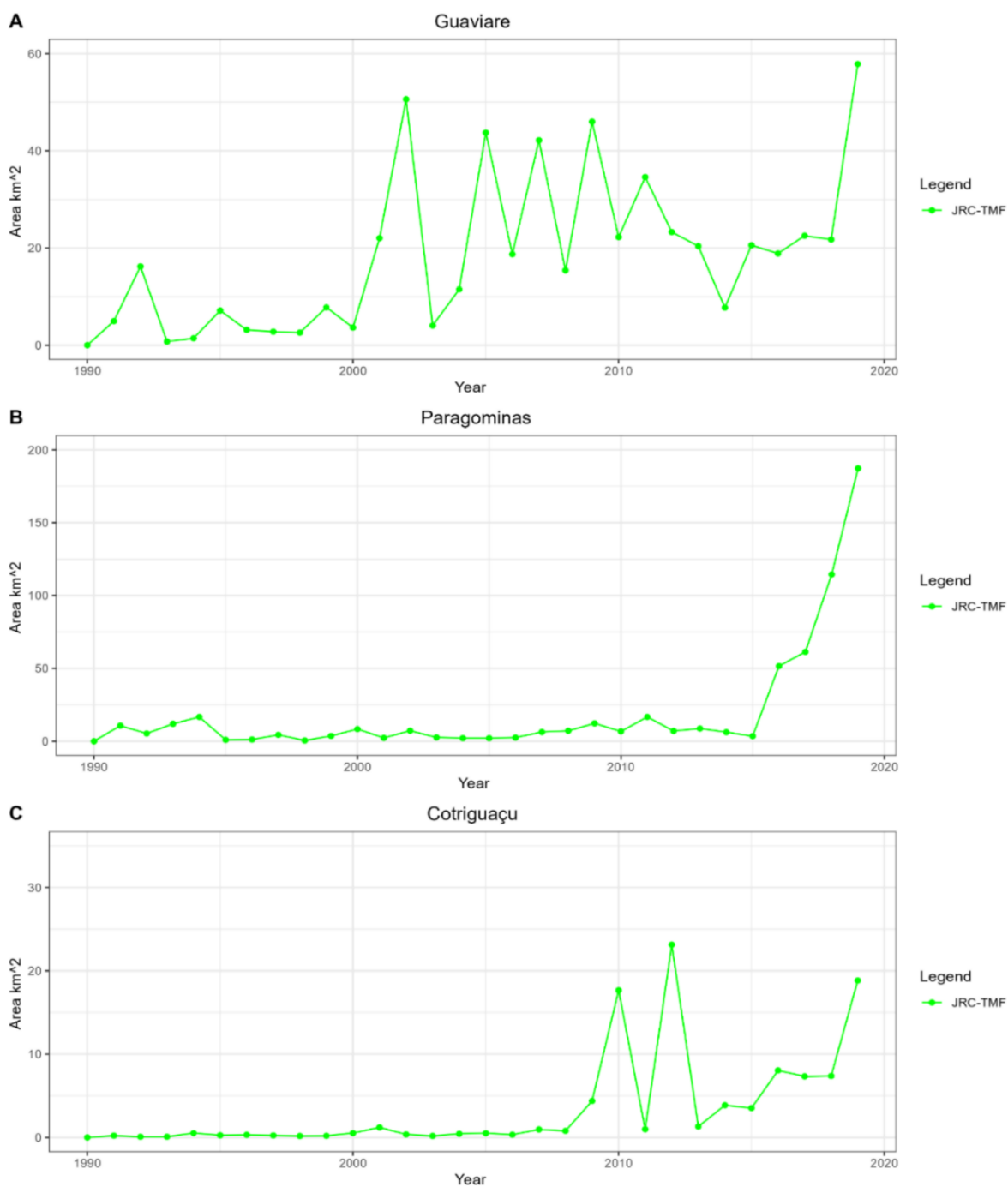


Figure 26: Annual area of secondary forest in three subnational jurisdictions of the Amazon: Guaviare, Paragominas, and Cotriguaçu. Data source: JRC-TMF.

The spatial distribution of secondary forests in Guaviare is relatively dispersed, with notable concentrations in the southern municipality of Miraflores and scattered patches across Calamar and San José del Guaviare. These regenerating areas are often found adjacent to previously deforested zones, suggesting a pattern of regrowth following land abandonment (Fig. 27).

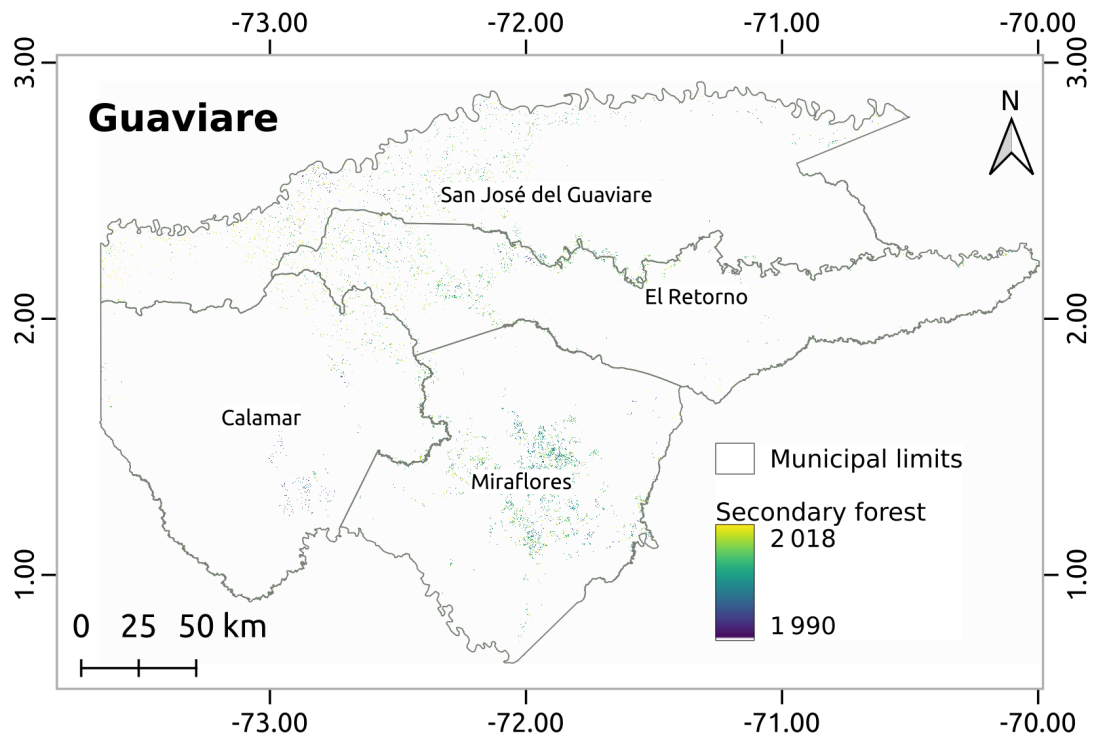


Figure 27: Spatial distribution of secondary forest in the department of Guaviare, Colombia, from 1990 to 2021. Data source: JRC-TMF.

In Paragominas, secondary forest regeneration is distributed unevenly, with a notable concentration in the northeastern and southeastern portions of the municipality. These areas align with zones of previous deforestation and pasture abandonment. The presence of secondary forest is especially evident in mosaic patterns near agricultural zones, suggesting a transition dynamic driven by land-use shifts (Fig. 28).

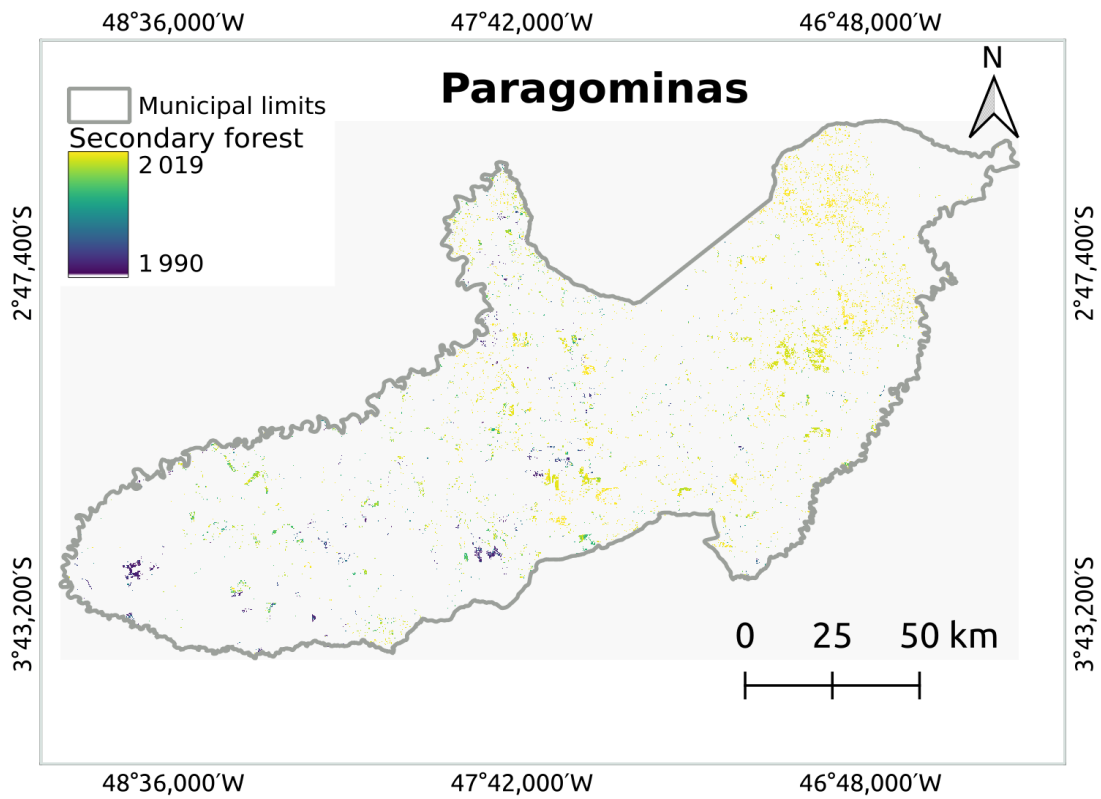


Figure 28: Spatio-temporal distribution of secondary forest in Paragominas, Brazil from 1990 to 2021. Data source: JRC-TMF.

In Cotriguaçu, secondary forest regeneration is sparsely distributed, with small patches primarily located in the southern and southwestern regions of the municipality. These areas likely reflect processes of pasture abandonment or low-intensity land use that have enabled natural regrowth (Fig. 29).

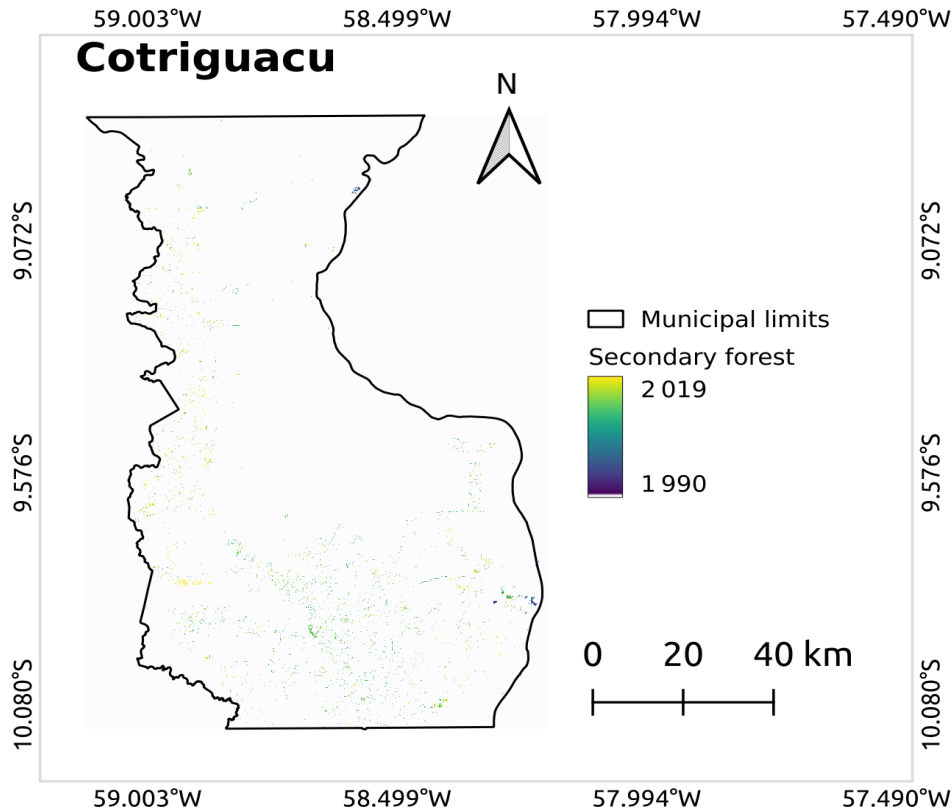


Figure 29: Spatio-temporal distribution of secondary forest in Cotriguaçu, Brazil from 1990 to 2021. Data source: JRC-TMF.

1.2.3.4 Land use and land cover transition

The analysis was done for two periods of time: conversions between 1991 and 2005, and conversions between 2005 and 2021. We divided the land-use transition analysis into two periods based on methodological criteria and key historical contexts that influenced forest cover dynamics in these territories. First, the year 2005 marks a turning point in environmental policy, particularly in Brazil and other Amazonian countries. In Brazil, for instance, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) initiated in 2004 began to show significant impact from 2005 onward, ushering in a period of stricter environmental regulation and improved enforcement. Second, from a data perspective, both periods have a comparable duration of approximately 15 years, which ensures temporal consistency in the transition analysis and minimizes potential biases associated with unequal time intervals.

In Guaviare (Fig. 30), between 1991 and 2005 the dominant land-use transformations were the conversion of undisturbed forests into degraded forests (2.21% of the total undisturbed forest area) and pastures (1.83%). The conversion into mosaic land uses represented only 0.80%. After 2005, the conversion of undisturbed forests into pastures increased significantly (3.14% of the total undisturbed forest area, respectively), and the conversion into degraded forest also increased slightly (2.38%). The conversion part into mosaic of uses remained low (0.57%). From 2005 to 2021, approximately 31% of the degraded forests were converted into pastures, while 63% remained unchanged. Secondary forest growth due to abandoned pastures represented 17.64% of the 2005 pasture area.a.

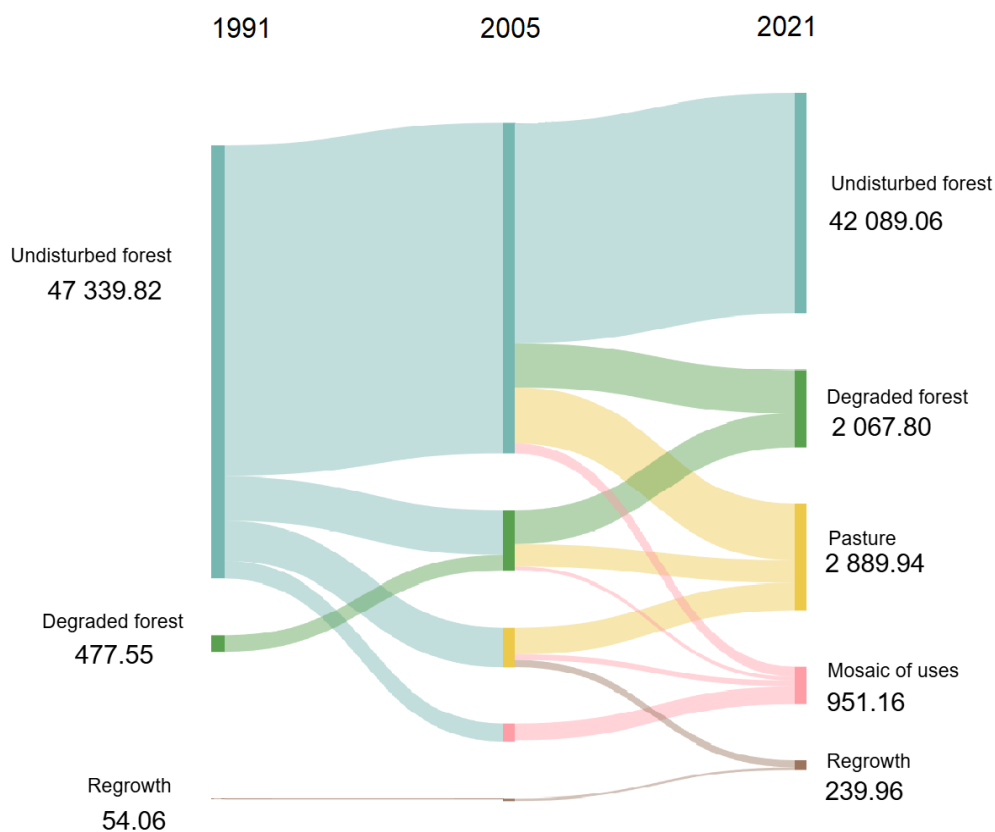


Figure 30: Sankey diagram showing the total area (km²) covered by each land use in 1991, 2005 and 2021 at the department of Guaviare-Colombia. Source: TMF data and MapBiomias.

In Paragominas (Fig. 31), between 1991 and 2005 the dominant land use transformation was the conversion of undisturbed forests into pastures (12.99% of the total undisturbed forest area), followed by conversion into

degraded forests (8.18%). Conversion to soybean cultivation was low (0.21%). After 2005, the conversion of undisturbed forests into degraded forests (13% of the total undisturbed forest area), and soybean plantations (1.6%) increased significantly, while the conversion into pastures decreased to 3.89%. Between 2005 and 2021, 27% of the pasture were converted into soybean plantations. Regarding degraded forests, approximately 23.16% were converted into pastures, while 76.83% remained unchanged. Secondary forest growth due to abandoned pastures represented 13.02% of the 2005 pasture area.

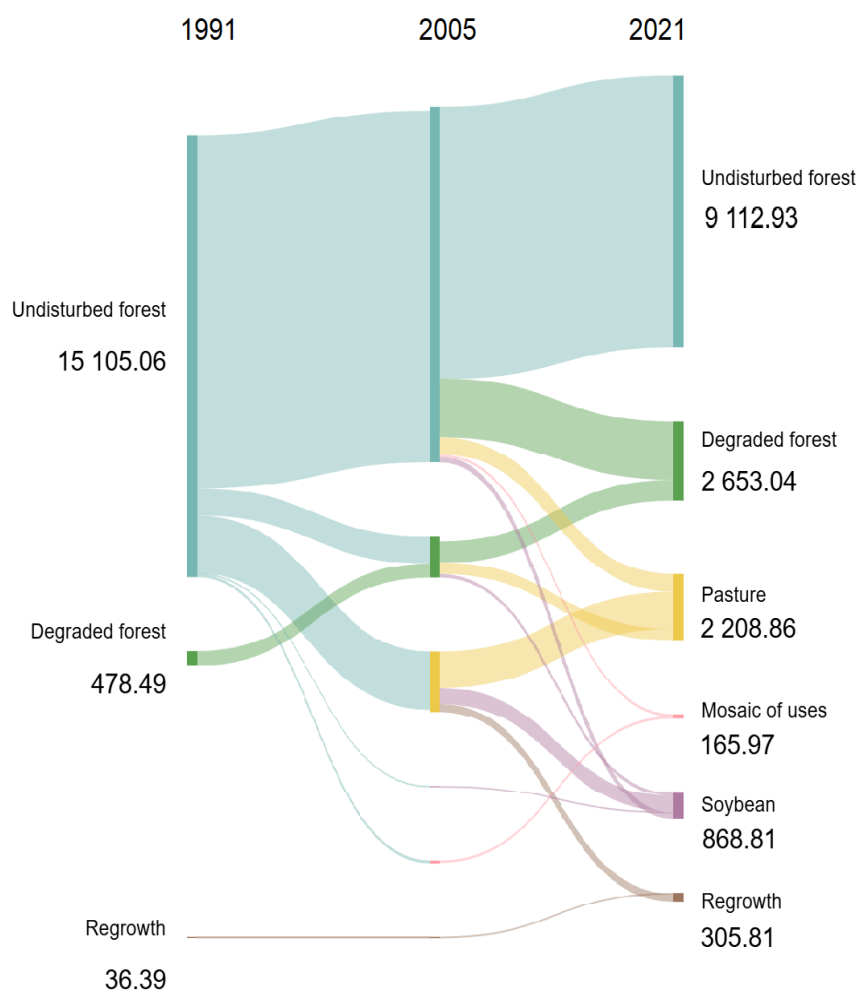


Figure 31: Sankey diagram showing the total area (km²) covered by each land use in 1991, 2005 and 2021 at the municipality of Paragominas-Brazil. Source: TMF data and MapBiomas.

In Cotriguaçu (Fig. 32), during both analyzed periods (1991–2005 and 2005–2021), the conversion of undisturbed forests into pastures was the dominant

land-use transformation, accounting for 13.25% and 8.65%, respectively. This was followed by the conversion into degraded forests (2.77% for 1991-2005, and 2.28% for 2005-2021). Additionally, from 2005 to 2021, secondary forest growth due to abandoned pastures represented 4.13% of the 2005 pasture area.

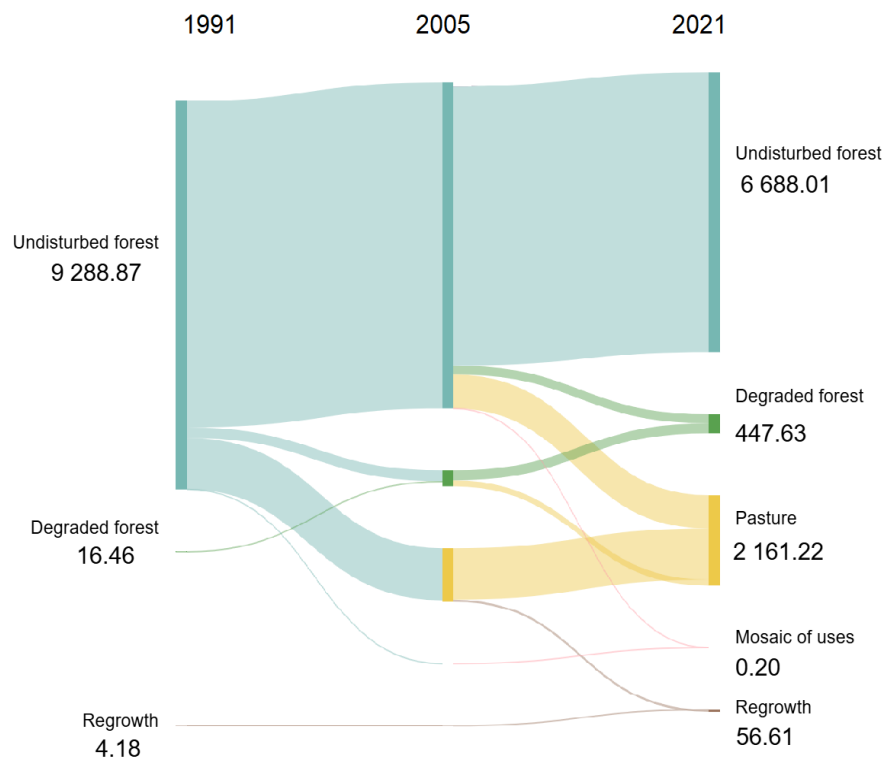


Figure 32: Sankey diagram showing the total area (km²) covered by each land use in 1991, 2005 and 2021 at the municipality of Cotriguaçu-Brazil. Source: TMF data and MapBiomias.

1.2.3.5 Fire statistics at the site level

Forest loss due to fire

Forest area loss caused by fires, based on GLAD-Fire data, shows distinct patterns across the three territories (Fig. 33A). In the department of Guaviare, values remained low between 2001 and 2016 (1–10 km²), but increased significantly after 2016, reaching a peak of 32 km² in 2018. In Paragominas, losses were similarly low during the same period (1–17 km²); however, a sharp increase was recorded in 2016, with an area of 998 km² affected, equivalent to 5% of the territory. That year, a strong El Niño event occurred, significantly reducing rainfall in the eastern Amazon, including the Paragominas region. In Cotriguaçu, forest loss remained consistently low, ranging between 1 and 10 km² throughout the 2001–2021 period.

Burned area of all land uses

The burned area across all land uses, based on MODIS-Fire data for the period 2001–2021, exhibits heterogeneous interannual patterns in the three analyzed territories (Fig. 33B). In the department of Guaviare, three significant peaks were recorded in 2004, 2007, and 2018, with values of 630 km², 929 km², and 1 155 km², respectively, with the latter representing 2% of the total territorial area. In Paragominas, variations were also heterogeneous, with two major peaks in 2005 and 2015, reaching 630 km² and 1 337 km², respectively. Meanwhile, Cotriguaçu displayed two distinct phases: an initial phase of increase between 2001 and 2006, peaking at 312 km² in 2006, which represented 3% of the territory, followed by a second phase of decline from 2008 to 2021, with an average of 77 km², except for a sharp increase in 2015 and 2017, reaching 228 km² and 202 km² respectively.

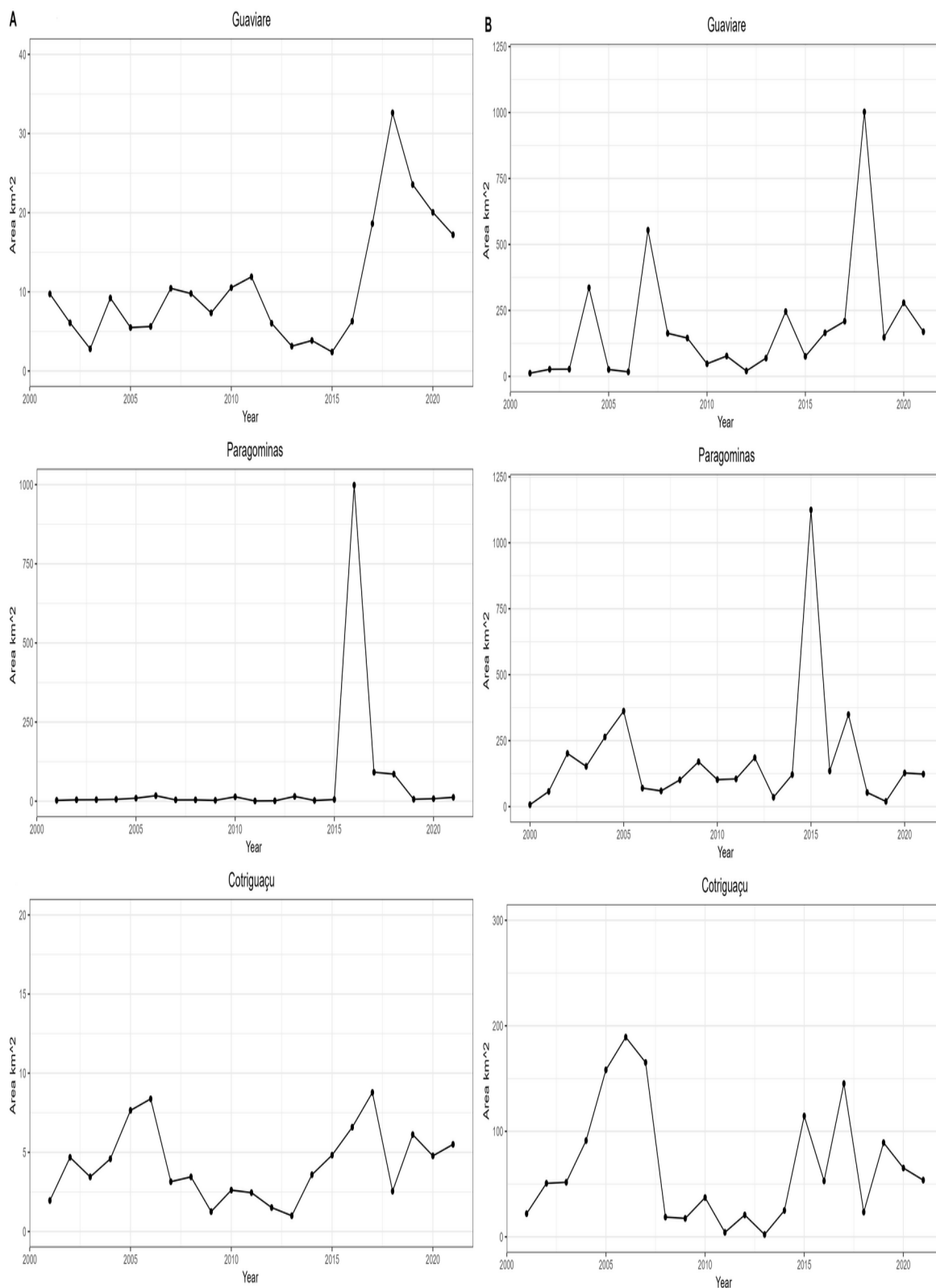


Figure 33. Annual burned area for three subnational jurisdictions in the Amazon: Guaviare, Paragominas, and Cotriguaçu. Data Source: A) Glad-fire and B) MODIS-Fire.

In Guaviare, the spatial distribution of forest fires detected by GLAD-Fire from 2001 to 2021 is concentrated primarily in the northwestern and central regions of the department. Fire occurrences appear more frequently in areas near San José del Guaviare and along the borders of Calamar and El Retorno municipalities. Fires are sparse in the southeastern part, particularly in Miraflores (Fig. 34).

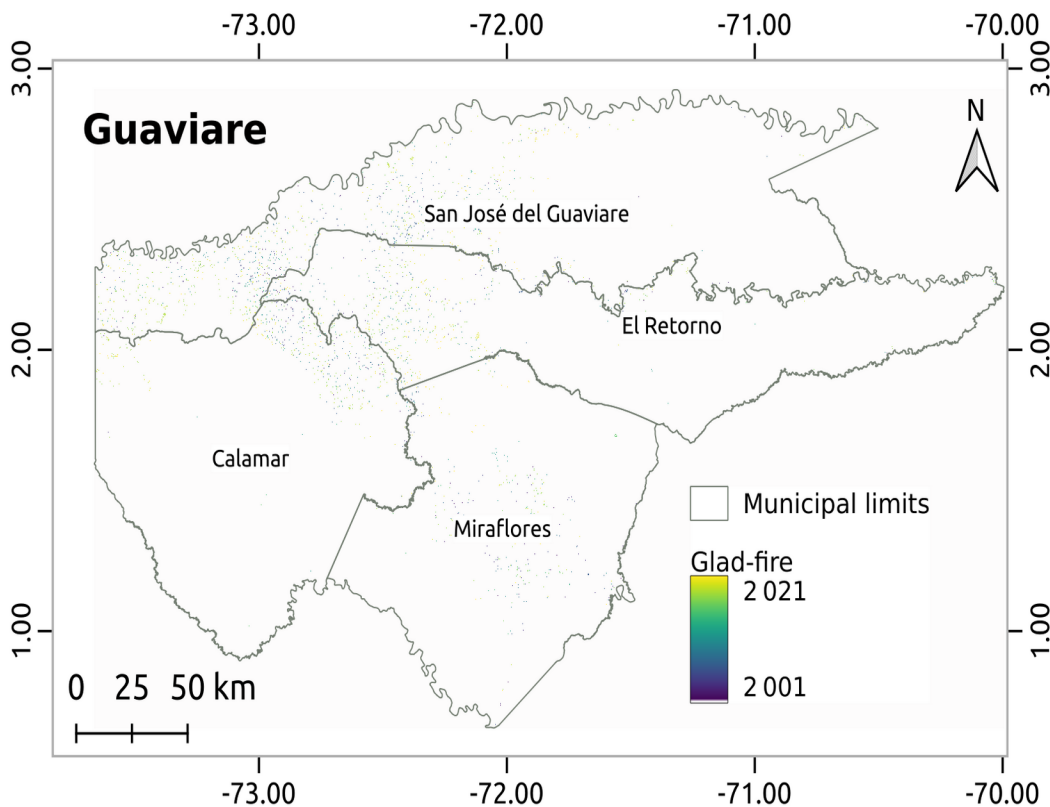


Figure 34: Spatial distribution of burned area in the department of Guaviare, Colombia, from 2001 to 2021. Data source: GLAD-Fire.

In Paragominas, the GLAD-Fire data show a pronounced concentration of fire activity in the central and northeastern zones, with significant burned areas also appearing in the southern portion. These regions overlap with landscapes dominated by pasture and agricultural expansion, where fire is often used as a land management tool. The intensity and extent of fires increased notably in 2015-2016, aligning with extreme drought conditions (Fig. 35).

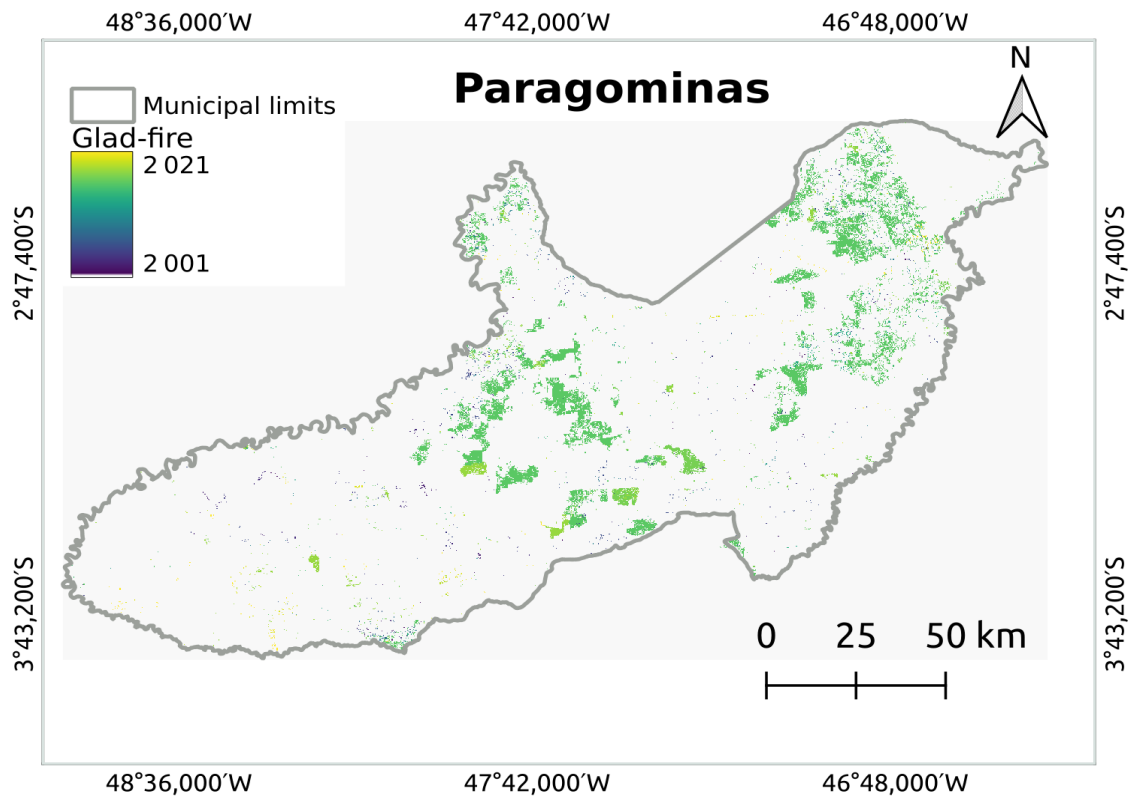


Figure 35: Spatio-temporal distribution of burned area in Paragominas, Brazil from 2001 to 2021. Data source: GLAD-Ffire.

In Cotriguaçu, the spatial pattern of fire occurrence from GLAD-Fire data reveals a scattered distribution, with hotspots concentrated in the southern and western zones of the municipality. These areas coincide with regions of greater deforestation and pasture establishment. Fire activity peaked around the mid-2000s and again in 2017 (Fig. 36).

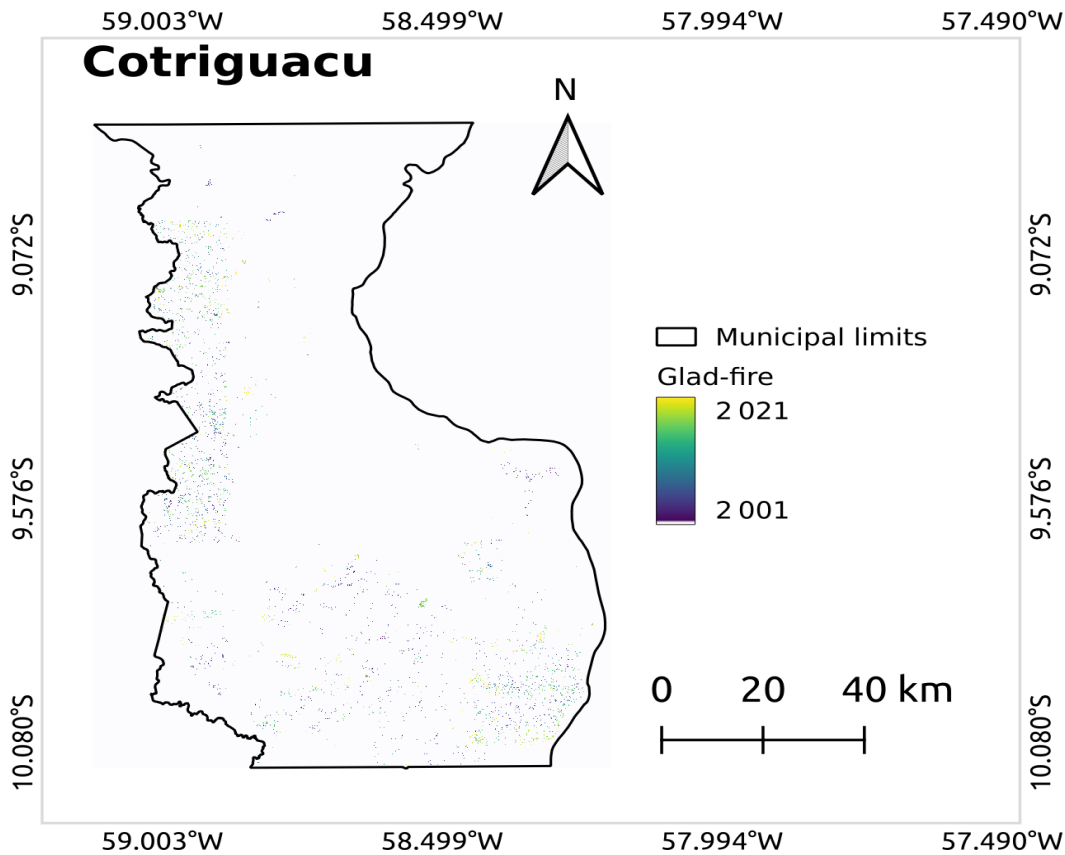


Figure 36. Spatio-temporal distribution of burned area in Cotriguacu, Brazil from 2001 to 2021. Data source: GLAD-Fire.

The spatial pattern of MODIS-fire in Guaviare reveals high fire density in the northwest and central-western regions, particularly around San José del Guaviare and the northern part of Calamar. These areas coincide with zones of active deforestation and land-use conversion. Fire activity extends into southern Miraflores, indicating ongoing forest disturbance in more remote areas. In contrast, the eastern and northeastern regions exhibit minimal fire presence (Fig.37).

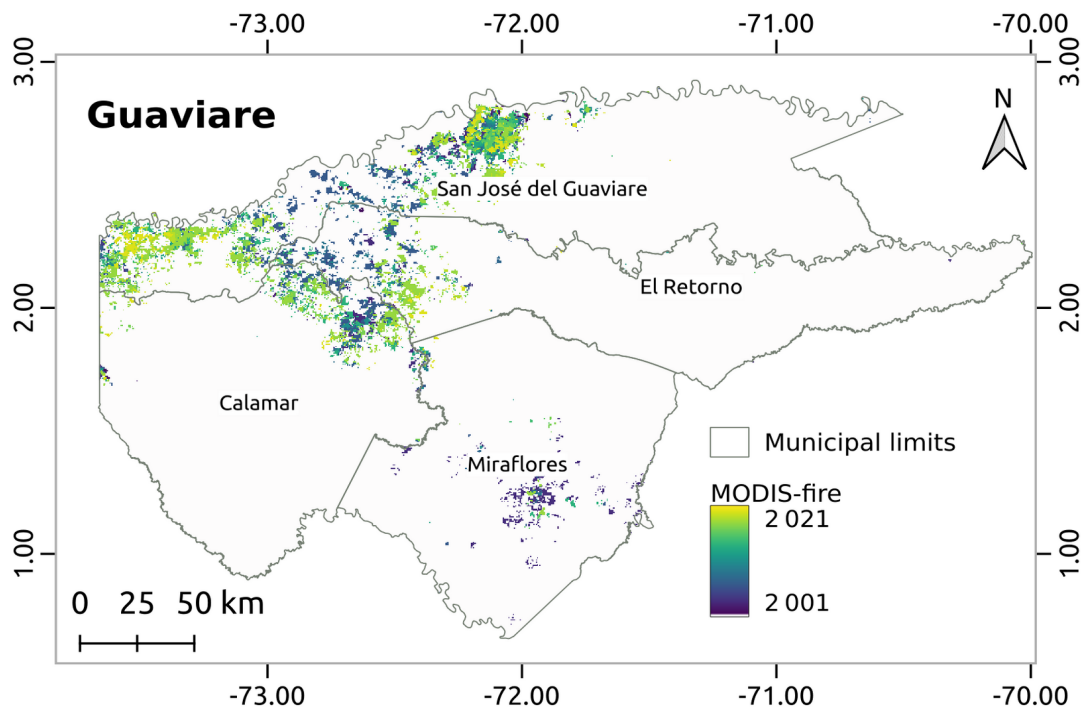


Figure 37: Spatial distribution of burned area in the department of Guaviare, Colombia, from 2001 to 2021. Data source: MODIS-fire.

The spatial distribution of MODIS-detected fire events in Paragominas shows a high concentration of fire activity in the central and eastern portions of the municipality. Several hotspots, particularly in the northeast and southeast, reflect recurring large-scale burning, likely associated with pasture management and agricultural practices. Fires are also scattered across the southwest, though with less density. The temporal spread highlights notable fire years such as 2015 and 2016 (Fig. 38).

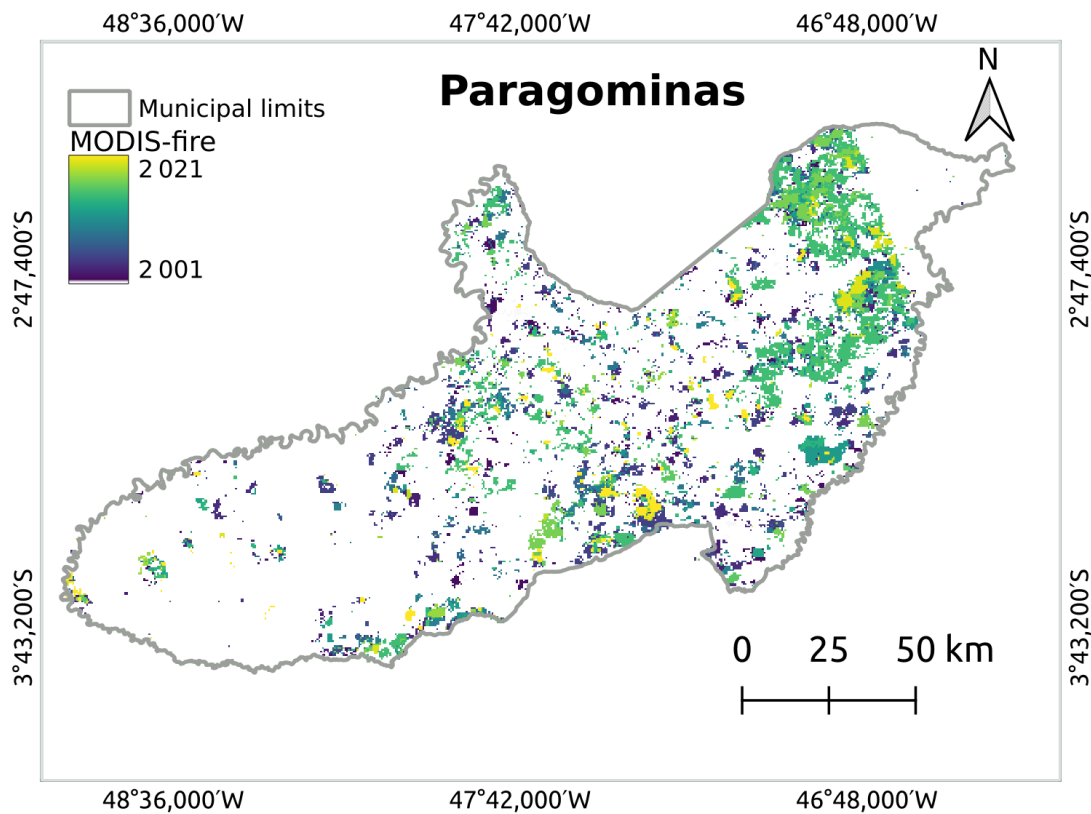


Figure 38: Spatio-temporal distribution of burned area in Paragominas, Brazil from 2001 to 2021. Data source: MODIS-fire.

The MODIS fire data for Cotriguaçu reveal two prominent hotspots of fire activity: one along the western flank and another in the southern portion of the municipality. These areas show recurrent fire detections throughout the study period, with intense events in 2005-2006 and 2015-2017. Fire events are largely concentrated in previously deforested zones, particularly where pasture dominate. In contrast, the northern and central core of the municipality exhibit sparse fire incidence (Fig. 39).

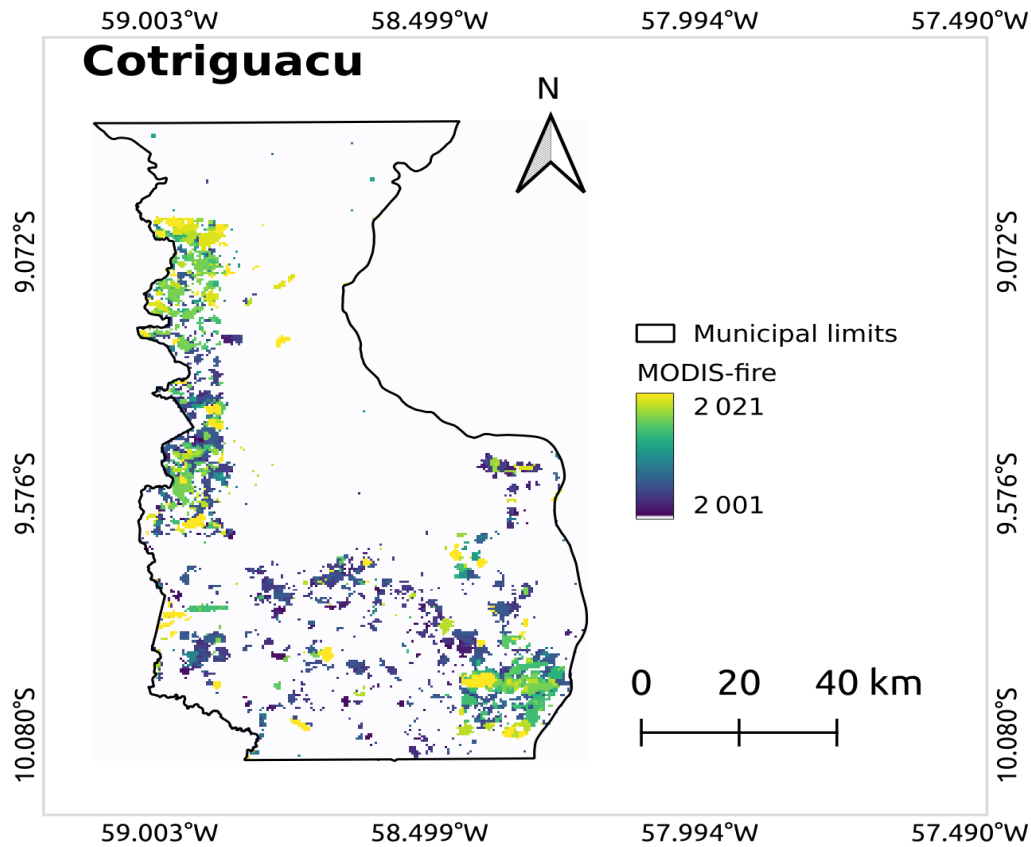


Figure 39: Spatio-temporal distribution of burned area in Cotriguaçu, Brazil from 2001 to 2021. Data source: MODIS-fire.

1.2.3.6 Fire statistics by forest classes

The forest area loss due to fire (GLAD-Fire) is analyzed for the three forest classes - undisturbed, degraded and regenerated forests - derived from the TMF database.

In Guaviare (Fig. 40), between the period 2001-2021, the burned area generally showed low values, under 16 km². However, we observed that the distribution of the burned area was primarily concentrated in degraded forests, with highest values recorded in 2018 and 2019 (burned areas of 15 km² and 10 km², respectively).

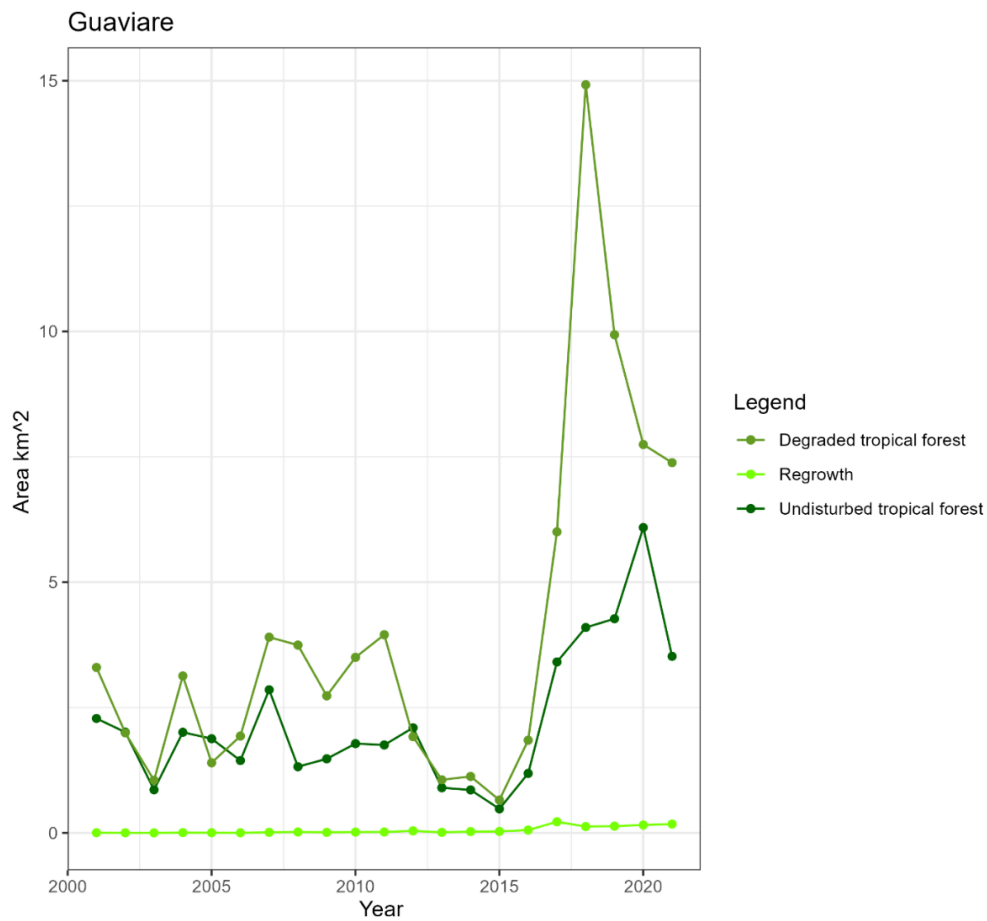


Figure 40: Distribution of burned area of different forest classes for the Guaviare Department, Colombia. Data source: GLAD-Fire, and TMF-JRC.

In Paragominas (Fig. 41), we observed that the distribution of burned areas showed low values for the three forest classes ($< 10 \text{ km}^2$), except for the year 2016 during which degraded forests recorded the largest burned area (842 km^2).

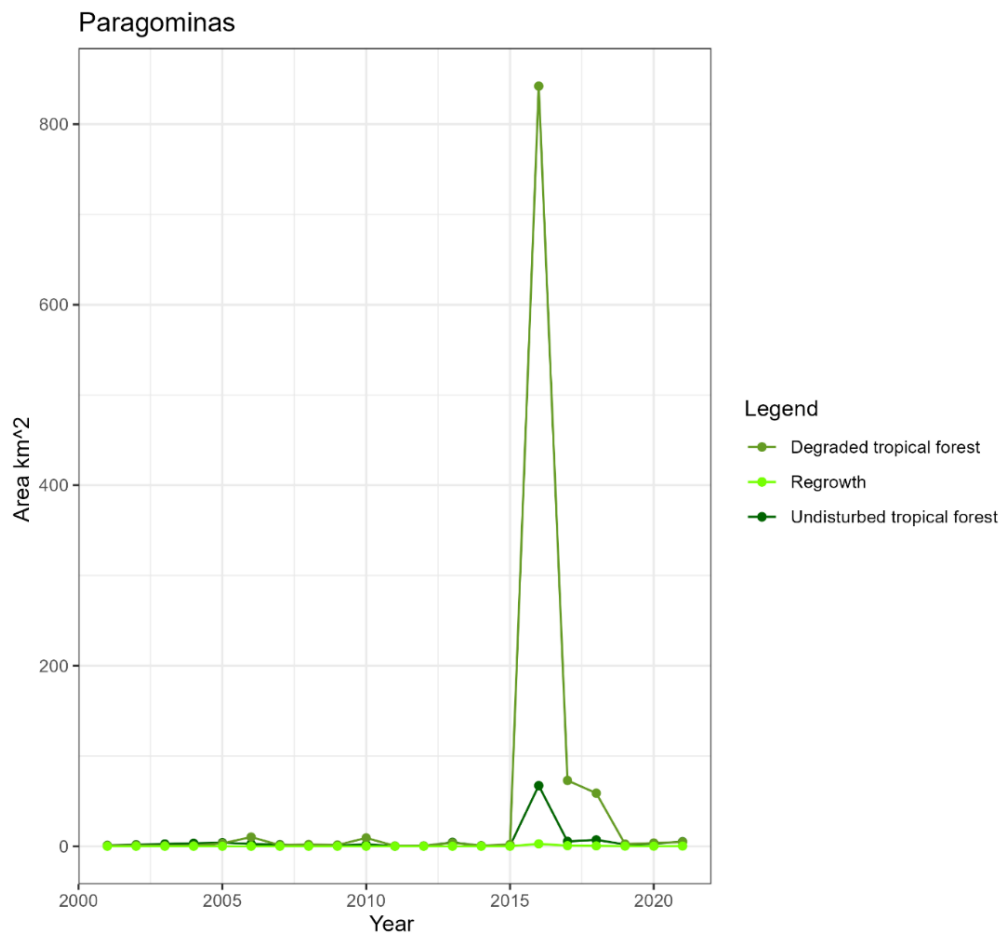


Figure 41. Distribution of burned area of different forest classes for the municipality of Paragominas, Brazil. Data source: GLAD-Fire, TMF-JRC, and MapBiomass.

In Cotriguaçu (Fig. 42), we observed that the distribution of burned area was low, with values under 3 km² for each forest class. Between 2014 and 2021, the burning forest area was primarily concentrated in degraded forests (Fig. 39).

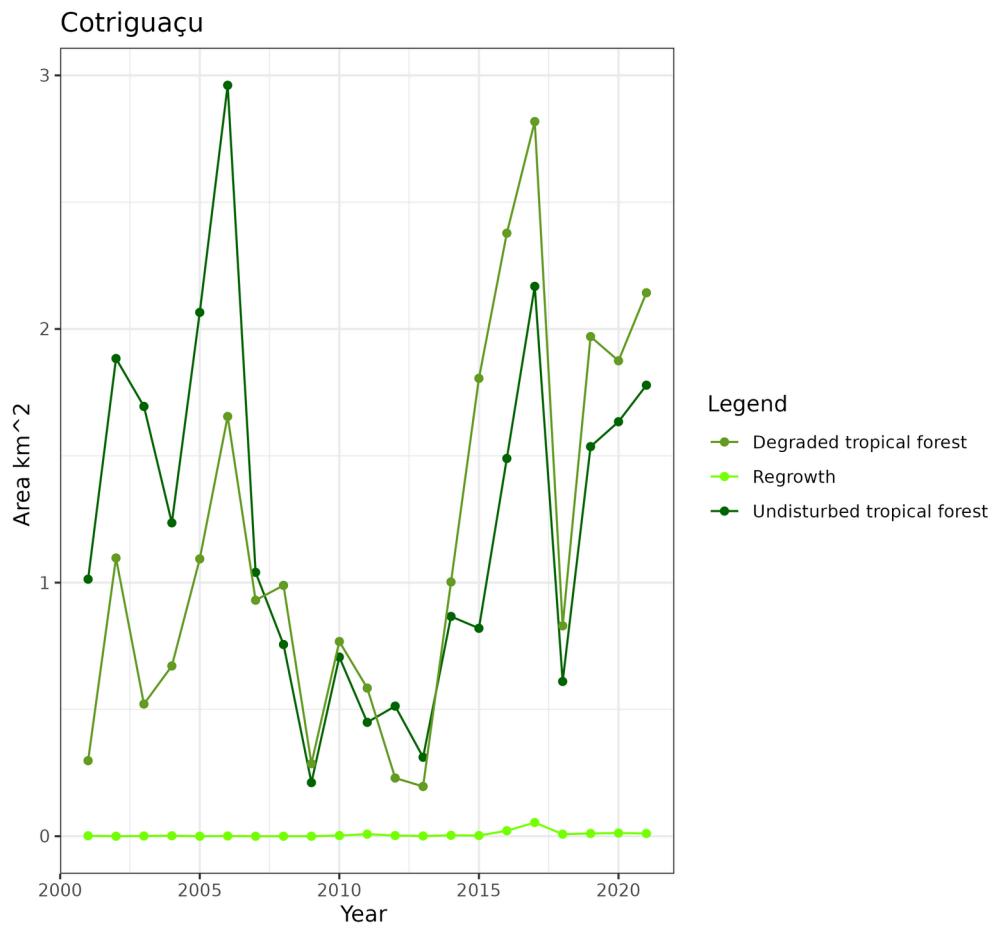


Figure 42: Distribution of burned area of different forest classes for the municipality of Cotriguaçu, Brazil. Data source: GLAD-Fire, TMF-JRC.

1.2.3.7 Fire statistics by land use classes

In Guaviare (Fig. 43), between 2001 and 2021, burned areas were recorded across various land use types, with pastures and undisturbed tropical forests being the most prominent. The distribution of burned area was dominated by pastures in the years 2007 and 2018, with areas of 336 km² and 571 km², respectively. Additionally, degraded forests also experienced a significant increase in burned area during those same years, with areas of 121 km² and 115 km², respectively.

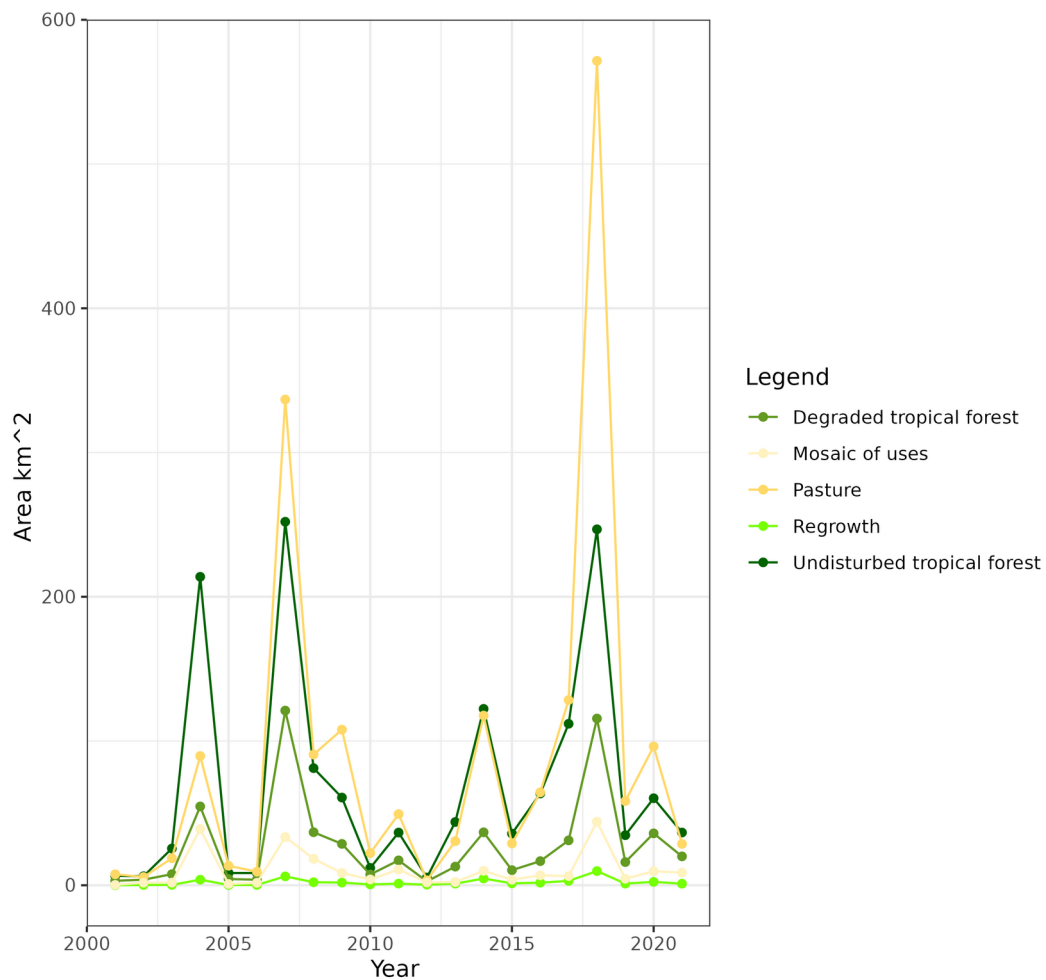


Figure 43: Distribution of burned area of different land uses for the Guaviare Department, Colombia, between 2001-2021. Data source: MODIS-Fire, TMF-JRC, and MapBiomas.

In Paragominas (Fig. 44), the distribution of burned area of different land uses was primarily concentrated in pastures and undisturbed forest during the period 2001-2021. The highest burned area values in pastures were recorded in 2005 and 2015, with areas of 257 km² and 612 km², respectively. Degraded and undisturbed forests also showed significant values in 2015, with burned areas of 263 km² and 411 km², respectively.

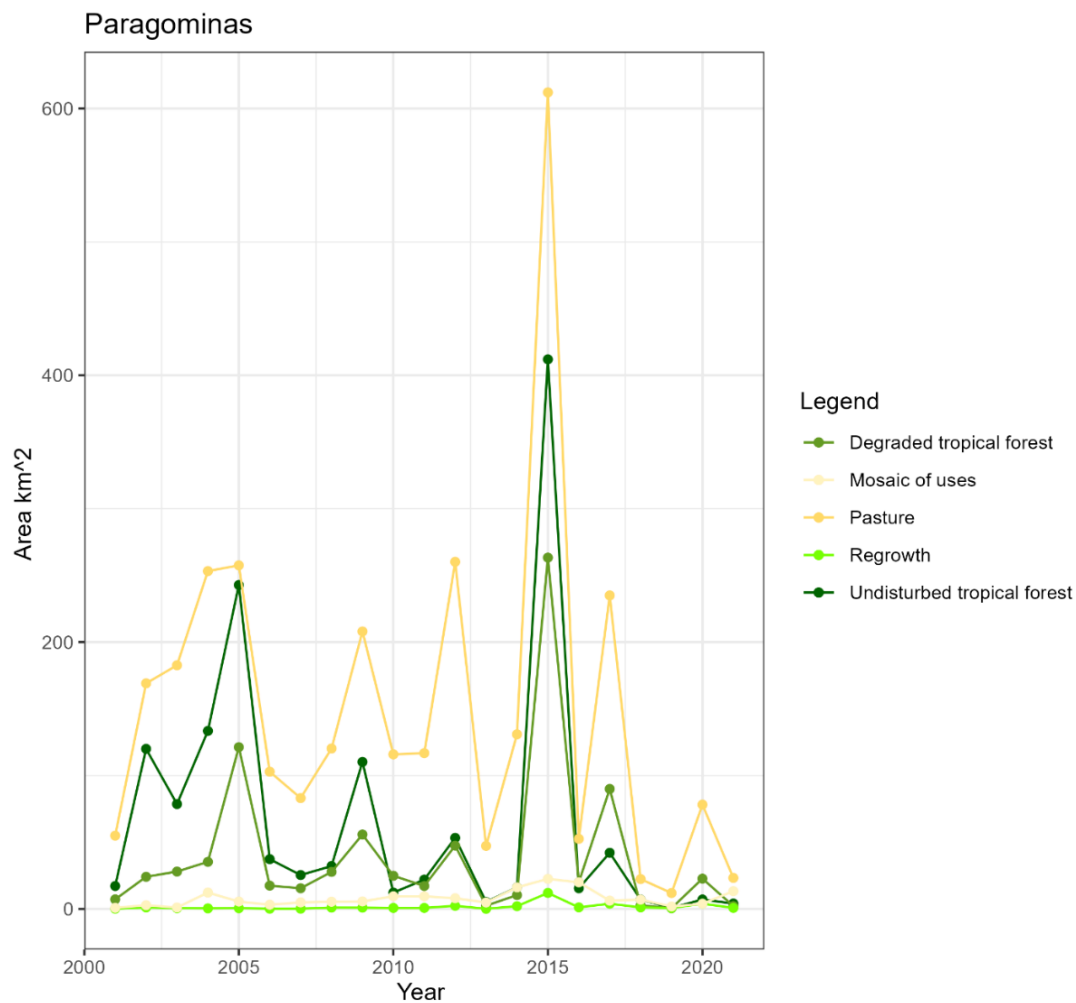


Figure 44: Distribution of burned area of different land uses for the municipality of Paragominas, Brazil, between the period 2001-2021. Data source: MODIS-Fire, TMF-JRC, and MapBiomias.

In Cotriguaçu (Fig. 45), we observed that the years 2005, 2006, 2015, and 2017 were notable for having significant burned areas, especially in pastures with values of 169 km², 194 km², 172 km² and 160 km², respectively. Additionally, between 2001 and 2007, undisturbed forests also showed significant values of burned areas. In contrast, between 2008 and 2021, most of the burning was concentrated in pasture areas with peaks in 2015 and 2017 (172 km² and 160 km², respectively).

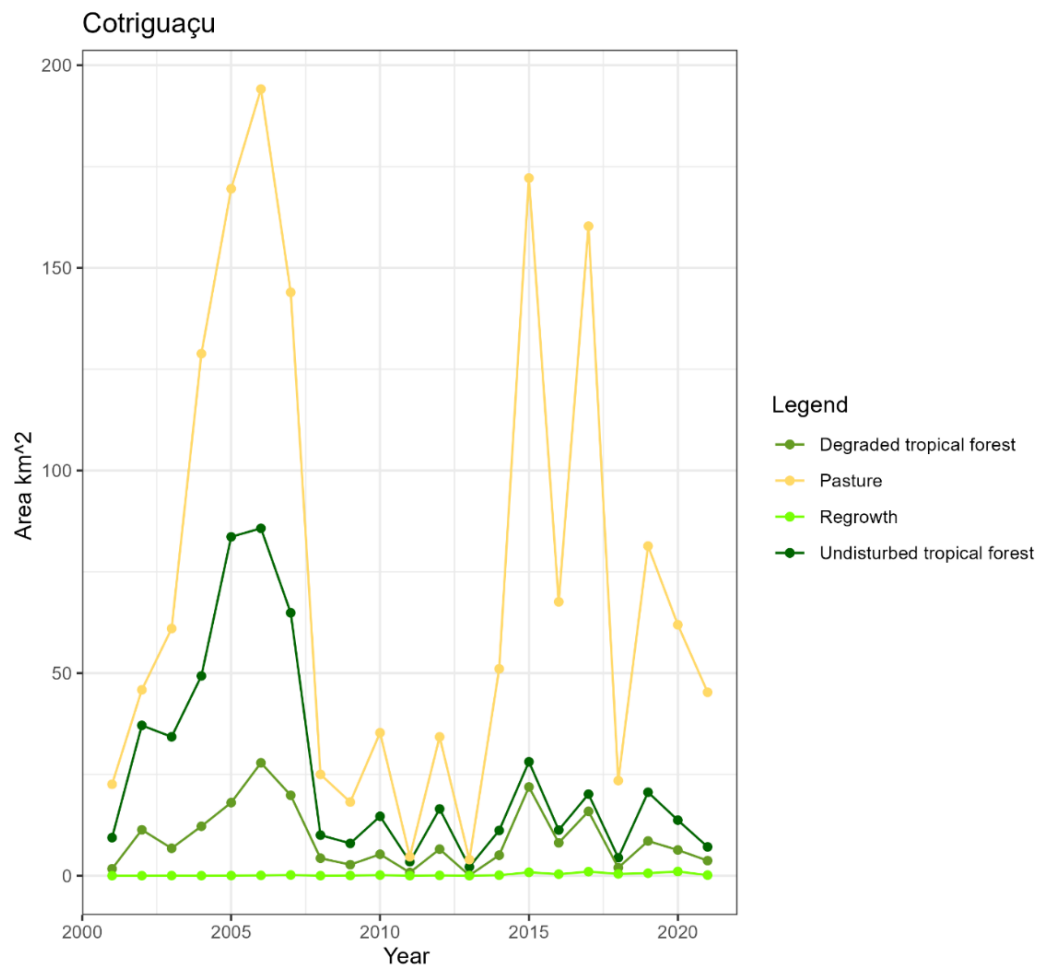


Figure 45: Distribution of burned area of different land uses for the municipality of Cotriguaçu, Brazil, between 2001-2021. Data source: MODIS-Fire, TMF-JRC, and MapBiomas.

1.2.3.8 Climate statistics at the site level

Precipitation

The Amazon region is susceptible to climatic anomalies associated with the El Niño–Southern Oscillation (ENSO), particularly during El Niño events, which often lead to severe drought conditions across vast portions of the basin. According to Brando et al. (2019), El Niño intensifies temperature and reduces precipitation, leading to soil moisture deficits, increased tree mortality, and heightened fire susceptibility in tropical forests. These climatic stressors not only affect forest health but also exacerbate deforestation and degradation dynamics by increasing the likelihood of large-scale wildfires. The 2015–2016 El Niño event, for instance, triggered some of the most extreme drought-related disturbances observed in recent decades, causing extensive forest canopy loss and weakening forest resilience (Esquivel-Muelbert et al., 2019).

In Guaviare, between 2003 and 2021, the average annual precipitation ranged from 2 593 mm to 3 571 mm. Higher precipitation levels were concentrated in the southeastern and central areas of the department, while the northwest recorded lower values. The spatial distribution of standard deviation revealed greater variability in the southwest of the territory, with values reaching up to 413 mm. In contrast, the northern and eastern zones showed more stable precipitation patterns with deviations as low as 164 mm (Fig. 46).

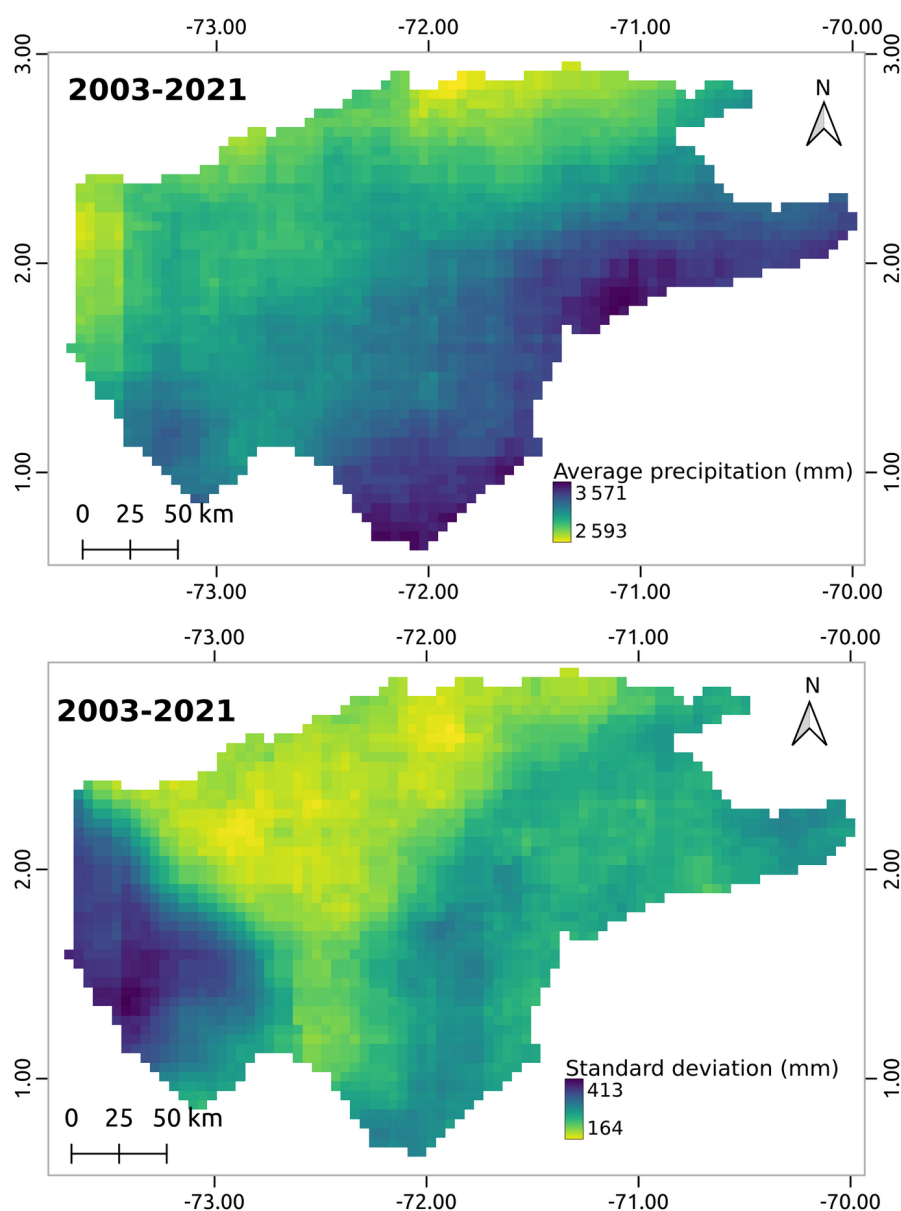


Figure 46: Spatial distribution of average precipitation and standard deviation map for the period 2003-2021 in the department of Guaviare, Colombia. Source: CHIRPS data.

In Paragominas, between 2003 and 2021, the spatial distribution of average annual precipitation exhibited a clear west-east gradient. The western portion of the municipality showed higher precipitation values, reaching up to 2 848 mm, while the eastern region presented lower values, with a minimum of approximately 1 697 mm. Regarding variability, the standard deviation of precipitation ranged from 200 mm to 425 mm, with the highest interannual

variability concentrated in the southwest and southeastern parts of the territory (Fig. 47).

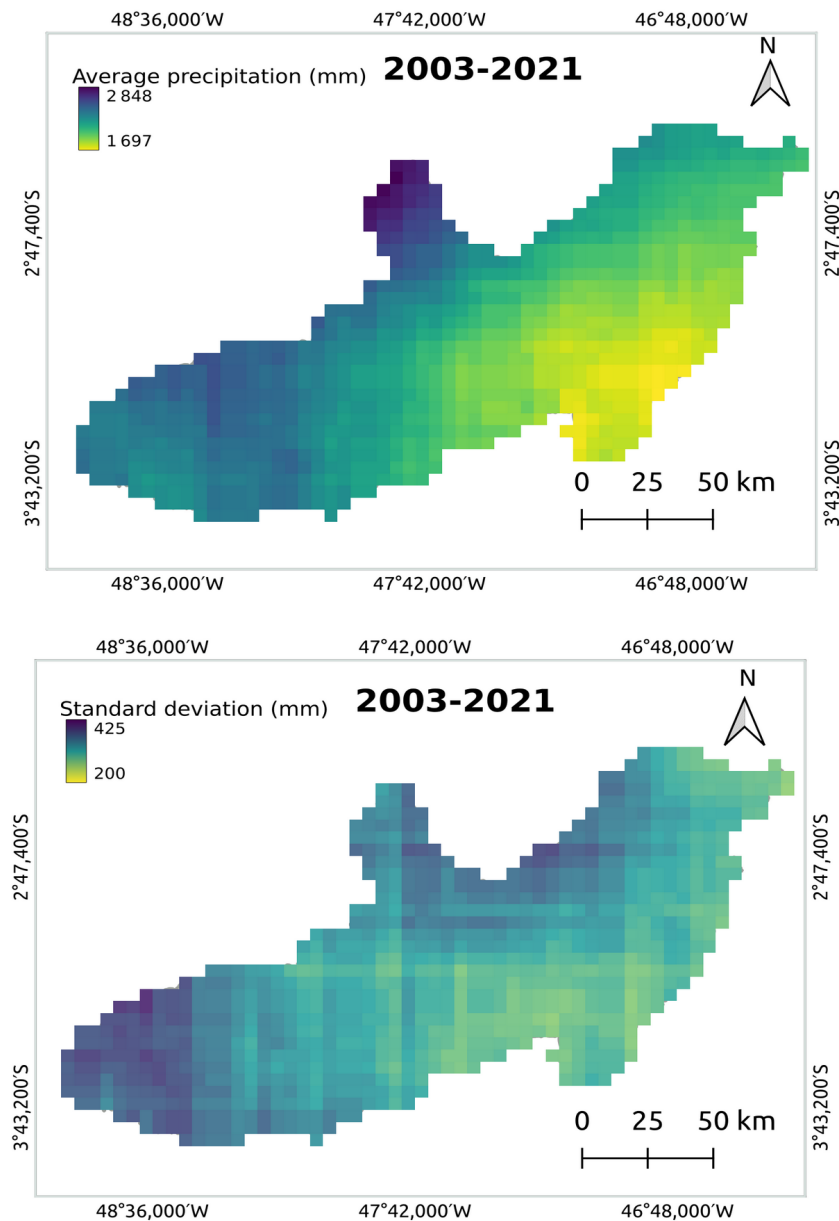


Figure 47: Spatial distribution of average precipitation and standard deviation map for the period 2003-2021 in the municipality of Paragominas-Brazil. Source: CHIRPS data.

In Cotriguaçu, between 2003 and 2021 exhibited spatial variation in average annual precipitation, with values ranging from 2 133 mm to 2 349 mm (Fig. 28). Higher precipitation levels were concentrated in the northern part of the municipality, while lower values occurred in the southern region. The standard deviation of precipitation across the same period ranged from 137 mm to 250 mm. Greater interannual variability was observed in the northern portion of the

territory, whereas the southern areas exhibited more stable rainfall patterns (Fig. 48).

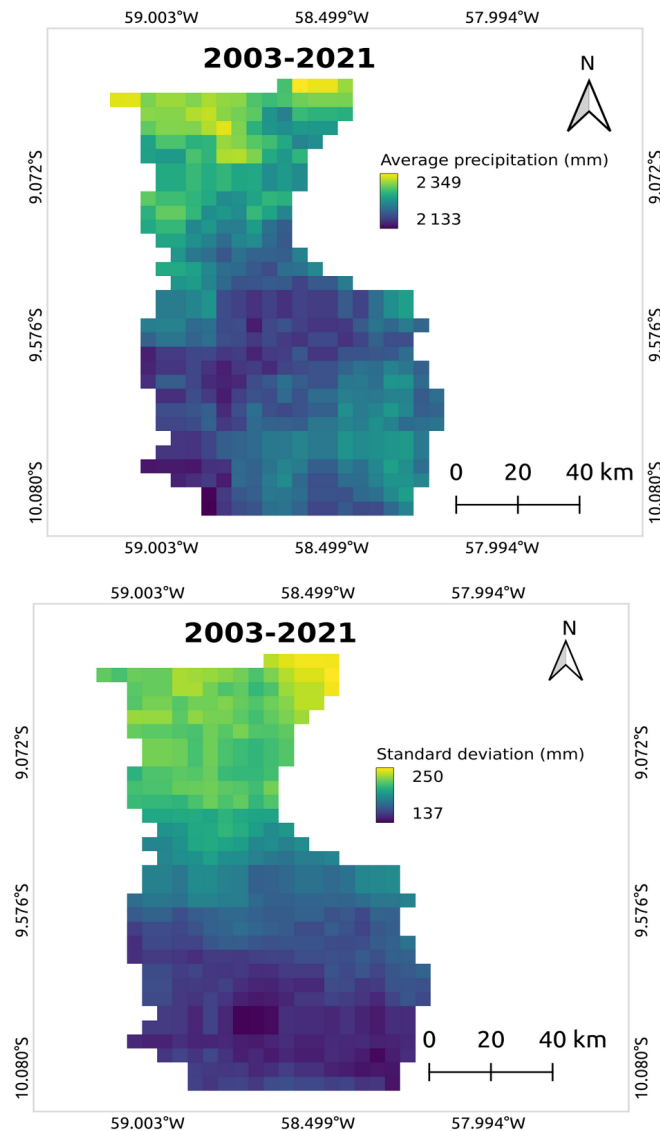


Figure 48: Spatial distribution of average precipitation and standard deviation map for the period 2003-2021 in the municipality of Cotriguaçu-Brazil. Source: CHIRPS data.

Precipitation in Guaviare, Paragominas, and Cotriguaçu displays temporal and spatial variabilities (Fig. 49). In Guaviare, annual precipitation showed marked variability between 2003 and 2021. The year 2003 recorded the highest precipitation of the period, with an average of approximately 3 700 mm, a minimum of around 2 900 mm, and a maximum exceeding 4 100 mm. In contrast, significant reductions were observed in 2008 and 2017. In 2008, the average precipitation was approximately 3 100 mm, with minimum and maximum values of around 2 600 mm and 3 600 mm, respectively. In 2017,

the average dropped to about 2 800 mm, with a minimum near 2 500 mm and a maximum around 3 300 mm. By 2021, Guaviare showed a partial recovery in precipitation levels, reaching an average of approximately 3 000 mm, with a minimum of about 2 700 mm and a maximum of 3 400 mm.

In the municipality of Paragominas, annual precipitation between 2003 and 2021 displayed significant interannual variation (Fig. 49). During the first period 2003-2012, the year 2003 registered precipitation levels, with an average of approximately 1 880 mm, a minimum near 1 490 mm, and a maximum around 2 350 mm. In contrast, 2012 recorded the lowest precipitation for that period, with an average of approximately 1,650 mm, ranging from a minimum of 1 200 mm to a maximum of 2 300 mm. In the second period, 2013-2021, a sharp decline was observed in 2015, with the lowest precipitation in Paragominas, particularly in relation to extreme dry events such as those linked to El Niño. The average that year dropped to approximately 2 100 mm, with a minimum around 1 850 mm and a maximum close to 2 650 mm. By 2021, precipitation partially recovered, reaching an average of about 2,250 mm, with a minimum of 1 800 mm and a maximum of 3 000 mm.

In the municipality of Cotriguaçu, annual precipitation data between 2003 and 2021 revealed low spatial variability (Fig. 49). In 2003, the average precipitation was approximately 2 240 mm, with values ranging from a minimum of about 2 100 mm to a maximum close to 2 400 mm. By contrast, the year 2005 recorded lower precipitation, with an average of approximately 1 950 mm, a minimum around 1 850 mm, and a maximum of 2 020 mm. Other drop in precipitation was observed in 2015, marking one of the driest years in the time series for Cotriguaçu. That year, the average precipitation fell to around 2 020 mm, with a minimum near 1 900 mm and a maximum of 2 150 mm. In comparison, precipitation levels increased again by 2021, with an average of approximately 2 400 mm, a minimum of around 2 350 mm, and a maximum reaching 2 900 mm.

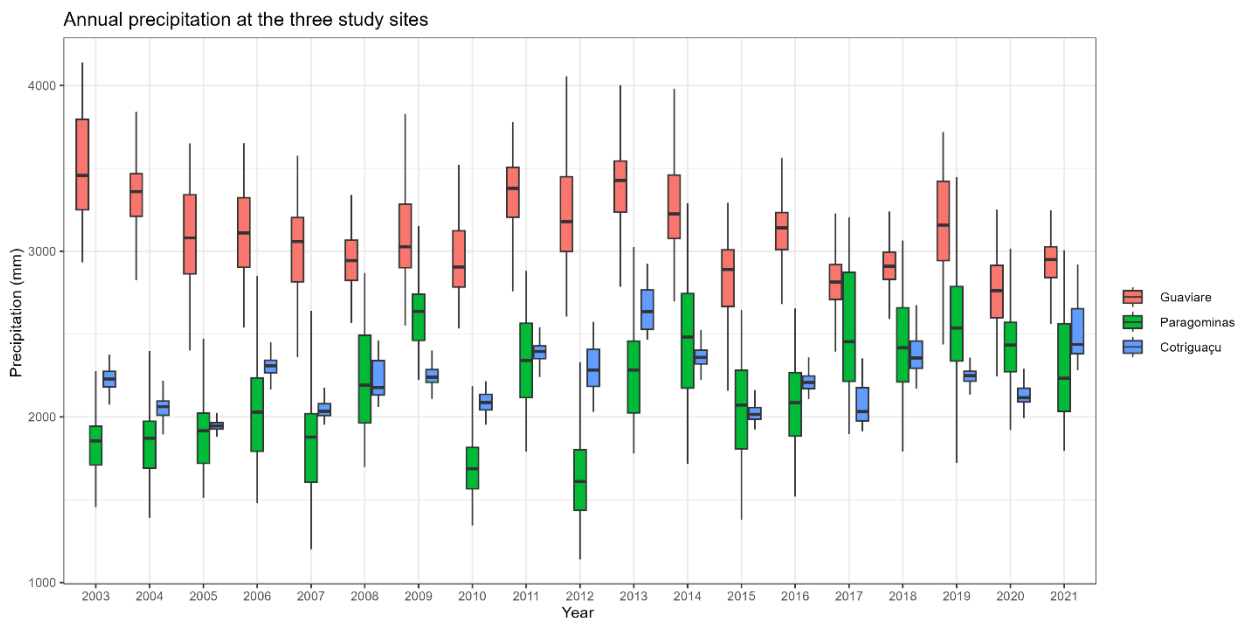


Figure 49: Boxplots of the annual precipitation for the three subnational jurisdictions (Guaviare, Paragominas and Cotriguaçu). Source: CHIRPS data.

1.2.3.9 Climate statistics and land use

In the department of Guaviare annual precipitation in 2003 showed notably high values across all forest cover types (Fig. 50A). For undisturbed forests the mean precipitation reached approximately 3 500 mm. Regrowth forests followed with an average of around 3 490 mm. Degraded areas had a slightly lower average of about 3 210 mm while deforested areas recorded the lowest average among the four classes at approximately 3 200 mm.

Divergences of rainfall of four land use types: Undisturbed, Degraded, Deforested, and Regrowth over Guaviare, Colombia, between 2003 to 2021. The differences represent how undisturbed forest cover and secondary regrowth have superior microclimatic conditions conducive to the preservation of rainfalls. Contrarily, land degradation and forest loss reveal diminishing precipitation as a result of increased surface temperatures, decreased evapotranspiration, and irregular hydrology. Land use contrast reveals how local climatic control may be altered by forest change.

The annual precipitation records over Paragominas, Brazil, show the fluctuations in rainfall over land-use types (Fig. 50B). Generally, the undisturbed forest has received a comparatively higher median precipitation 2

500 mm, especially during the period 2014–2019 , followed closely by regrowth recorded a mean of about 2 400 mm. The degraded and deforested areas tend to record comparatively lower precipitation with high variability and lower medians for some years, approximately 2010 and 2012. Despite inter-annual variability, undisturbed and regrowth classes appear more resilient to rainfall decline.

In Cotriguaçu, rainfall variability is illustrated by land-use categories (Fig. 50C). Undisturbed forests had a mean of around 2 400 mm with a range from ~2 270 mm to ~2900 mm. Regrowth forests had a similar average of about 2 390 mm, degraded forests had an average of 2 300 mm, and deforested areas had an average of 2 200 mm. The deforested and degraded areas have relatively lower rainfall with high variability and lower medians degraded areas had an average of 1 970 mm (min ~1 900 mm, max ~2 300 mm), and deforested areas had an average of 1 960 mm (min ~1 900 mm, max ~2 250 mm).

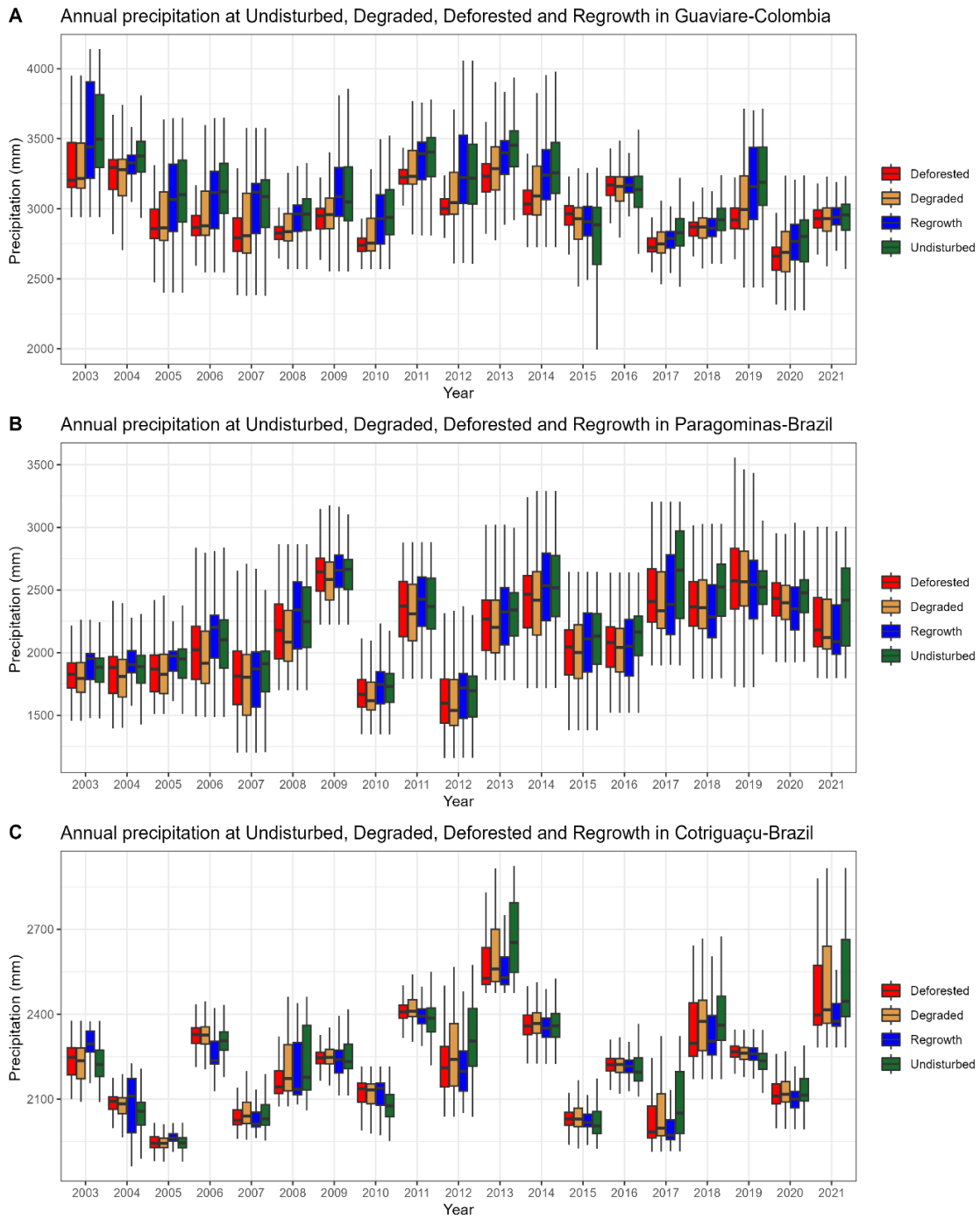


Figure 50: Annual precipitation calculated over deforested, degraded, regrowth and undisturbed areas in the three subnational jurisdictions between 2003 – 2021: a) Guaviare, b) Paragominas and c) Cotriguaçu. Source: CHIRPS data.

1.2.4 Discussion

Dynamics of deforestation: analyzing historical trends in Guaviare, Paragominas and Cotriguaçu

The areal pattern of forest cover loss in Guaviare is an indication of its complex socio-political and land-use history. Forest cover loss came before important access routes, particularly where colonization and infrastructure growth were heightened during the 1980s and 1990s, like around San José del Guaviare. State-sponsored colonization initiatives promoted expansion and, after that, coca production expansion. The 2016 peace agreement was historic, but it also increased deforestation since groups pulled out and land grabbing on a large scale set in.

Our data in Guaviare confirm previous studies that state armed conflict temporarily suppresses deforestation by holding territories (Dávalos et al., 2011; Christiansen et al., 2022). As documented in San José del Guaviare, the initial growth of the 1980s–1990s was interrupted at the peak of the conflict, in line with overall trends in the Colombian Amazon (Murillo-Sandoval et al., 2020). Our work extends this, however, by demonstrating the reversibility of the impact: the resulting power vacuum from the 2016 peace deal unleashed a cycle of forest clearing. This abrupt change corroborates the hypothesis that weak land governance frameworks within peace processes can potentially lead to land rushes (Baptiste et al., 2017).

The deforestation front has progressively expanded into westward through Calamar, with recent hotspots indicating ongoing pressure in forest reserve. This pattern suggests a combination of spontaneous colonization, weak enforcement of land tenure, and insufficient institutional control. The expansion into forest reserves in Calamar reveals the state's inability to replace the territorial control previously exercised by the FARC, highlighting that formal peace has not translated into effective environmental governance (Armenteras et al. 2019; Negret et al. 2019; Murillo-Sandoval et al. 2022).

The dynamics of deforestation in Paragominas peaked in 2004, leading to the municipality's inclusion in the blacklist of the Brazilian government. Yet, from 2008 onward, the implementation of the "Green Municipality" program marked

a significant turning point. This program led to a substantial decline in deforestation rates, largely due to improved environmental monitoring, the widespread adoption of the Rural Environmental Registry (CAR), and enhanced compliance with environmental laws. The initial success of the "Green Municipality" program (2008–2015) demonstrates that it is possible to govern the environment through public–private partnerships (Piketty et al., 2015). These institutional efforts consolidated pasture expansion and predisposed shifts towards soybean cultivation on previously deforested lands, reducing direct pressure on intact primary forest.

In Cotriguaçu, the rate of deforestation indicates a progressive expansion of the agricultural frontier, especially between 2001 and 2006, with heavy deforestation in private lands and settlement areas. The boom in 2001–2006 overlaps with Brazil's Plano Amazônia Sustentável (2003), which spurred infrastructure projects without robust safeguards, accelerating land conversion in settlement areas (Fearnside, 2005). The second group, Agrarian reform settlements (e.g., INCRA settlements) became hotspots for deforestation as colonists cleared forest for subsistence in the presence of limited technical support (Brandão and Rist, 2020). As a result, this expansion phase created fragmentation thresholds (>50% of forest loss) that persist to the current times, undermining watershed connectivity and fire resilience (Tritsch & Arvor, 2016).

The deforestation dynamics in Cotriguaçu reflect a high dominance of primary forest to pasture conversion, which mirrors national Amazonian land-use change trends. It is a central part of a broader, larger-scale historical process in which cattle ranching is simultaneously a productive venture and a strategy of occupation for the region, particularly on the border (Margulis, 2004; Bowman et al., 2012). These instances demonstrate that deforestation is not only a consequence of uncontrolled occupation but also has its roots in policy errors, market-driven forces, and ambiguity regarding land tenure (Fearnside, 2001; Godar et al., 2014). Thus, it can address deforestation from a territorial perspective, considering the socio-political processes that influence land-use patterns.

Although Cotriguaçu was added to Brazil's deforestation blacklist in 2008, its institutional and territorial response lagged behind the early examples, such as Paragominas. Poor institutional and territorial capacity, along with disjointed stakeholder engagement, slowed the construction of effective forest governance for several years. However, since 2015, Cotriguaçu has been involved in the state-level "Produce, Conserve, and Include" (PCI) policy of the Mato Grosso government, aiming to balance agricultural production with environmental conservation and social integration (Strassburg et al., 2017). The integration facilitated the enforcement of key governance tools, including the Rural Environmental Registry (CAR), enhanced satellite monitoring, and dialogue among landowners, NGOs, and state agencies. CAR's introduction increased transparency over land-use processes and pressured compliance with the law, especially in those areas targeted by enforcement efforts (Börner et al., 2015; Stickler et al., 2013). As challenging as it remains, particularly for enforcement and socio-environmental justice, the PCI initiative was an important step toward reconciling Cotriguaçu's landscape management with overall sustainability goals and multi-level governance (Nepstad et al., 2014). The Cotriguaçu case demonstrates how late entrants can progressively reshape the local government through state-supported innovation and institution-building learning.

Understanding the dynamics of forest degradation in Guaviare, Paragominas and Cotriguaçu

Guaviare forest degradation exhibits a spatial distribution that coincides with, but also exceeds, deforestation hotspots, suggesting that disturbances do not always result in the complete clearing of the forest in these areas. Degradation is most apparent in zones of more established colonization and agricultural expansion, where selective logging, fire use in pasture maintenance, and edge effects along forest patches are prevalent. In particular, vast expanses surrounding Calamar and northern Miraflores have a long history of repeated bouts of degradation. While the literature has focused mainly on deforestation (Hansen et al., 2013), our data reveal that forest degradation is another critical process. This spatial trajectory, often overlooked by national data sources, exposes a key vulnerability: post-conflict policies fail to recognize that

degraded forests serve as “entry points” for illegal agricultural conversion (Murillo-Sandoval et al., 2023).

Regarding forest degradation in Paragominas, the data indicate a general occurrence in the north and eastern parts of the municipality, in areas that have not yet been fully deforested. This pattern shows the occurrence of activities such as logging, recurrent fire, and edge effects in fragmented forests. While the "Green Municipality" policy addressed gross deforestation, it did not account for degradation caused by fire and selective logging (Bourgoin et al., 2018), which still occurs in the municipality of Paragominas, compromising legal reserves and paving the way for future agricultural conversion.

Degradation of Cotriguaçu forest has a spatially fragmented signature closely associated with road-bordering areas and farms that involve repeated burning or selective logging. Over the last decade, degradation has intensified significantly through synergistic interactions among escaped fires and breakdown of formerly intact forest blocks. Smallholders' use of "queimadas" pasture management is extremely climate disturbance-sensitive: during El Niño droughts, 42% of such fires evolve into uncontrollable wildfires (Barlow et al., 2020). In particular, PRODES monitoring systems can detect obvious clear-cuts but miss ~90% of degradation processes, thereby causing considerable biomass loss (Tyukavina et al., 2017). Road-proximity effects: inside 500-800m halos around corridors like BR-174, selective logging severity is three times greater, triggering cascading edge effects that drive enhancement in degradation (Laurance et al., 2018).

Subnational dynamics of forest regeneration from Guaviare and Paragominas.

In Guaviare, forest regeneration remains spatially limited and mostly confined to abandoned pastures or mosaic landscapes with reduced accessibility. The spatial footprint of secondary forests is relatively small and fragmented, with notable patches in Miraflores. The forest regeneration observed in Miraflores, although positive, proves insufficient in the face of escalating degradation. This discrepancy contradicts the theoretical expectation that land abandonment

due to conflict would have resulted in widespread forest regeneration (Agudelo-Hz et al., 2023). An exception at remote mosaic sites suggests that location, rather than peace, governs the feasibility of regeneration, offering a critical piece of information for strategic restoration prioritization.

In Paragominas, the south and southwest regions have seen modest forest regeneration as landowners abandon pastures due to declining agricultural productivity, disincentives for land-use change, or shifts in their strategies. This regeneration aligns with global trends, where landowners first abandon marginal agrarian land as productivity declines (Grau and Aide, 2007). In southern Amazonia, this correlates with big cattle ranching systems becoming economically non-viable (Poccard-Chapuis et al., 2021). These are the regions showing the partial success of restoration and rule-of-law efforts under the "Green Municipality" program. Still, without ongoing incentives and governance structures to ensure long-term forest recovery, the fate of regrowth remains in doubt. Researchers document this finding in the context of controlling tropical forests, where command-and-control regulation is likely to fail without proper incentives for smallholders (Sills et al., 2014). Regulation alone rarely disrupts the economic drivers that lead to land abandonment (Smith et al., 2020).

Fire Dynamics: Interactions of agriculture, deforestation, and climate in Guaviare, Paragominas, and Cotriguaçu.

In Guaviare, the spatial and temporal patterns of fire activity reflect an increase in fire occurrence following the 2016 peace agreement, coinciding with higher rates of land transformation. The post-2016 increase in fires is not random: it reflects their deliberate use as a rapid mechanism for land-use change by new actors (cattle ranchers), facilitating forest-to-pasture conversion in Calamar and San José (Armenteras et al., 2019b). The spatial distribution of fires in the Calamar and El Retorno corridor overlaps with territories under the control of FARC and ELN dissident groups that profit from illegal land grabbing. Fire is being utilized as a tool of territorial control in new war economies (Armenteras et al., 2019c), more than as an agricultural practice.

In Paragominas, GLAD-Fire data quantify forest loss due to fire, highlighting 2015 as the most severe year of forest burning degradation, especially in previously degraded or pastures. The 2015 fire is a good example of how the synergistic interaction between extreme droughts (ENSO) and human landscapes plays out: agricultural/pasture dominance in the southeast created chronic flammable fuels (Aragão et al., 2018) making southeast Paragominas vulnerable to recurrent degradation (de Oliveira et al., 2023). MODIS-fire signals little background fire, while ground studies reveal persistent understory fires in patches of forest within agricultural matrices (Barlow et al., 2020). The regional aggregation in agricultural regions confirms fire remains deeply ingrained in local land uses apparently for pasture renewal and land clearing (Nepstad et al., 2001). Another study suggests conflict between traditional practices and conservation goals in the "Green Municipality" era (Osis et al., 2019). These dynamics underscore the need for integrated fire and land-use management policies, particularly in agricultural zones.

In Cotriguaçu, fire dynamics recorded by the MODIS-Fire and GLAD-Fire data sets exhibit an episodic but dynamic event course with temporal reinforcement in single years and spatial concentration in specific regions. MODIS-Fire indicated burned area peaks for 2005, 2006, 2015, and 2017 corresponding to record drought periods enabled by El Niño fluctuations (Jiménez-Muñoz et al., 2016). Such burns impacted only pasture biomes in the center and north, which reflects intentional management practices where smallholders utilize fire as a tool of vegetation management. Notably, fire densities across these agricultural frontiers suggest a land-use change process in which fire-active pastures serve as source areas of fire and may facilitate forest invasion (Arvor et al., 2014). Such spatial concentration along the productivity gradient reflects how biophysical constraints (soil quality) and infrastructural access (distance from the BR-174 highway) combine to shape fire regimes in frontier landscapes (Barber et al., 2014).

Our results indicated that the Paragominas and Cotriguaçu 2015 and 2016 fires are not caused by deforestation but are strongly correlated with Amazon drought, which in turn is influenced by the El Niño-Southern Oscillation (ENSO)

phenomenon. This is in line with the statements of Marengo et al. (2018) that they confirmed the Amazon region has warmed, the duration of the dry season increased, and there were increased climate extremes in 2005, 2010, and 2016 years and during previous droughts, the wet season started late and/or the dry seasons lasted longer. Complementing our study, Aragão et al. (2018) stated that the 2015 drought was the most intense of the 21st century because 1,8 million km² of an area equivalent to 43% of the Brazilian Amazon biome went through a positive fire anomalies have consistently increased from 11% in 2003 to 25% in 2015 in areas without deforestation, in this case, due to ENSO, can lead to chronic dry spells in the Amazonian forest, which can render the forest more susceptible to fire. Their studies confirm that there is a correlation between climatic trends and fire occurrences. The implications of these findings extend to ongoing discussions about climate change and its role in exacerbating extreme weather events. As global temperatures continue to rise, the frequency and intensity of ENSO events may increase, potentially leading to more severe droughts in the Amazon.

On the contrary, Silva et al. (2018) indicated that during 2015-2016, the South Amazonia region experienced positive fire anomalies; the region affected by fires had its peak of 6.4% of the Brazilian Amazon in 2015. Conversely, our study confirmed the relationship between deforestation and fire in Guaviare in 2017, both of which are increasing. This observation aligns with a range of studies that have sought to establish the intricate relationship between land use change and fire incidence in the Amazonian region. Armenteras et al. (2019) reported that fires increased from 2017 to 2018 in the 5 km buffer of protected areas, and the authors point to the emergence of new dynamics linked to FARC demobilization. This outcome in Guaviare supports the cogent call for comprehensive management strategies integrating fire prevention and sustainable land use.

Synthesis of indicators

We compared the available **deforestation** data for the Guaviare Department, Colombia, from 2002 using two databases: IDEAM and JRC-TMF. Both data sources are globally consistent and show similar values. Between 2002 and

2012, IDEAM presents mean values in two-year intervals, while JRC-TMF provides annual data for the entire time series from 1990 to 2021. A notable discrepancy appears in 2014, with JRC-TMF reporting higher deforestation values compared to IDEAM. These differences can be attributed to the distinct methodologies used: IDEAM applies a minimum mapping unit of 1 hectare, whereas JRC-TMF employs a finer resolution of 0.09 hectares.

We compared the available data on **deforestation** for the two Brazilian sites, Cotriguaçu and Paragominas since 1990 in three databases INPE-PRODES, MapBiomas and JRC-TMF. Although the three data sources differ in methodology, they show globally consistent patterns, with similar deforestation trends over time. Since 2015, the highest deforestation values are recorded by JRC-TMF and the lowest by INPE-PRODES. These discrepancies are mainly due to differences in satellite data sources (e.g., Landsat, Sentinel-1 and -2, CBERS) and methodological approaches (e.g., use of single images versus full time series, minimum detectable deforested area, semi-automatic versus fully automated processing). A key distinction of JRC-TMF is that it classifies severely and persistently burned forests as deforested areas. This methodological difference may account for the higher annual deforestation rates recorded by JRC-TMF in Paragominas between 2013 and 2016, and to a lesser extent in Cotriguaçu during the same period. This timeframe coincides with severe drought events in the Amazon (Esquivel-Muelbert et al., 2019).

For **forest degradation**, the only available data were from the JRC-TMF. Forest degradation in Guaviare shows similar annual values to those for deforestation, with two peaks: one in the 2000s and another in 2018. In Paragominas, degradation showed a significant peak in 2016. The years with the largest areas of degraded forest (2005-2006, 2010, 2015-2016) also correspond to those with the largest areas burned by fires in Pará state (Silva et al., 2023). Our results are consistent with previous studies, as we also observed peaks in forest degradation in Paragominas during 2006, 2010, and 2016. In contrast, degradation levels in Cotriguaçu were considerably lower than those of deforestation, suggesting a different disturbance dynamic.

Secondary forest has increased significantly since 2016 in Paragominas, it has remained constant in Guaviare in the last two decades, in Cotriguaçu it started in the 2010s but the annual area was limited. Overall, while deforestation and degradation continue to shape land-use changes in these jurisdictions, the presence of secondary forest regeneration suggests opportunities for ecological restoration.

The analysis of land-use transitions in Guaviare, Paragominas, and Cotriguaçu reveals significant trends in deforestation, forest degradation, and secondary forest regeneration over the past three decades. This analysis, taking into account land use transitions with historical maps, are excellent tools for understanding and planning sustainable land use over time (Merino et al., 2024; Peña-Cortés et al., 2020). Across all three regions, the conversion of undisturbed forests into pastures has been the predominant land-use change pushing cattle ranching to occupy new frontiers (McManus et al., 2016), although the intensity and timing of this process vary by location. In Paragominas, the dominant land-use transition initially involved the conversion of undisturbed forests to pastures, particularly between 1991 and 2005. In the following period 2005–2021, a significant portion of the remaining undisturbed forests was transformed into degraded forests. Over time, a new dynamic emerged, with secondary forest regrowth increasing primarily in areas previously occupied by pastures.

Concerning the fire activity, we found that the data on forest loss due to fire between 2001 and 2015 were low for all three territories, with the exception of 2016 for Paragominas and to a lesser extent for Guaviare in 2015. The large-scale fire recorded in Paragominas in 2016 affected extensive areas, primarily pastures and degraded forests. This event was not only captured in satellite records of fire related forest loss by GLAD-Fire but also reported locally as one of the most severe wildfires ever experienced in the municipality. The extreme climatic conditions associated with the El Niño event, including significant reductions in precipitation, contributed to the spread of the fire. In contrast, no significant changes were observed in Cotriguaçu.

The burned area across all land uses with Modis database showed significant values for all three sites: Guaviare, Paragominas, and Cotriguaçu. However, two peaks showed the highest values for Guaviare 2007 and 2018, while for Cotriguaçu, two peaks were also observed (2006 and 2017). Finally, in Paragominas, only one large peak occurred in 2015.

Climate: for precipitation at the territorial scale, interannual variations were observed in all three territories during the period from 2003 to 2021 and no spatial pattern according to land use.

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.

Keywords: deforestation; forest degradation; regrowth; Amazon; archetypes.

2.1 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., 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, 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, 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.

2.2 Materials and methods

2.2.1 Study sites

The study sites are three Amazon subnational jurisdictions (Fig. 51): 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 km², the population density is approximately 5.45 inhabitant/km² (IBGE, 2023). Colonization started with the opening of the Belem-Brasilia highway in the 1960s (Uhl and Guimaraes, 1989). Paragominas municipality experienced high rates of deforestation and degradation from the 1960s to 2005 (Tritsch et al., 2016). The majority of deforested land has been converted into pasture for cattle ranching. Until the 2010s, 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 2000s, 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., 2015). 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 km², the population density is approximately 1.21 inhabitants/km² (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 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 km², the population density is approximately 1.55 inhabitants/km² (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 km² was deforested, corresponding to 5.4% of the province. Over the period of 1982-2020, deforested areas (3494 km²) were mainly concentrated in the northwestern and southern regions. Since the 1980s, 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).

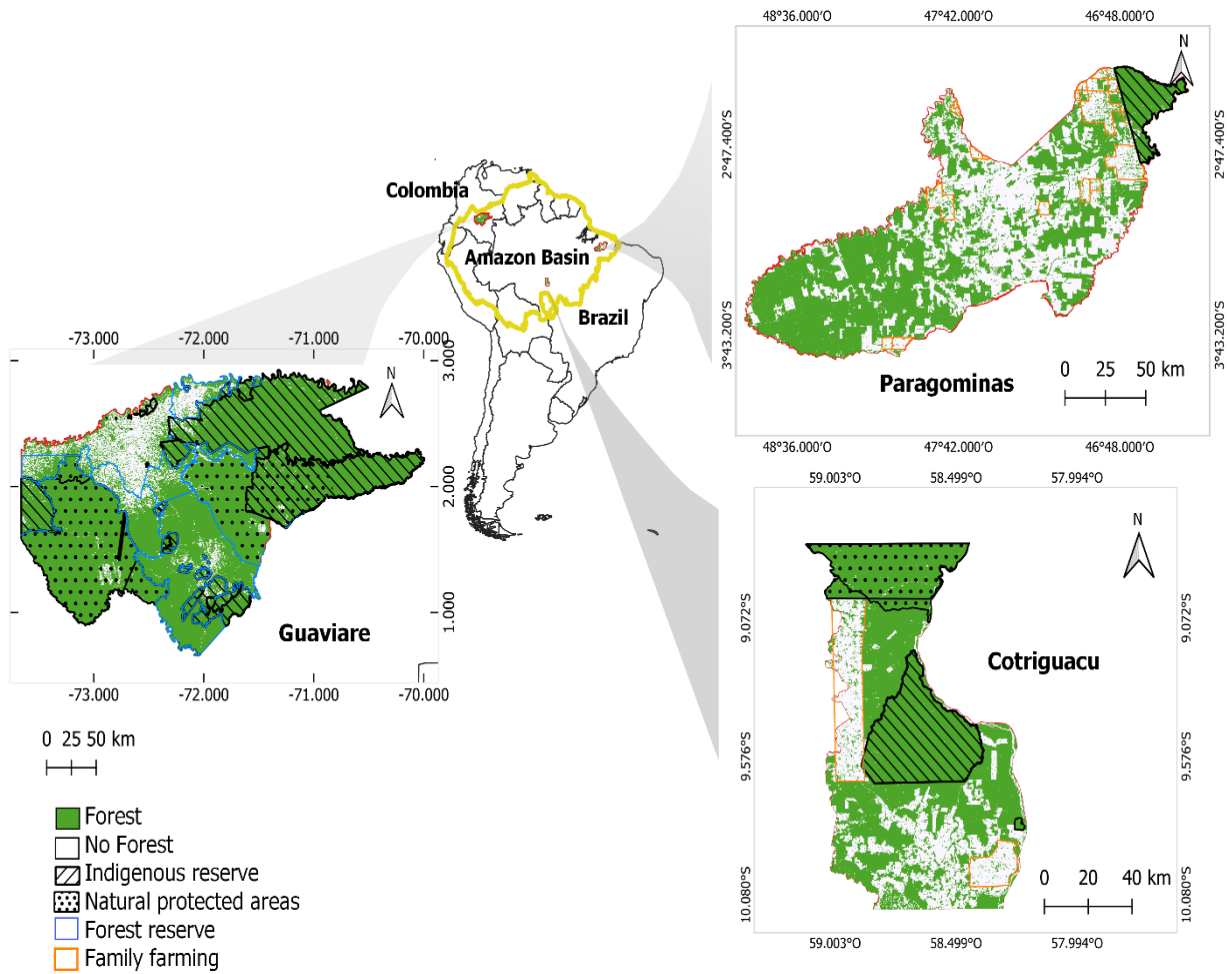


Figure 51: Location of the three study sites: the Department of Guaviare in Colombia and the municipalities of Cotriguacu and Paragominas in Brazil. Forested and non-forested areas are those recorded in 2022 (source: European Commission's Joint Research Centre, EC-JRC).

2.2.2 Methodology

Our framework analysis involved three main steps (Fig. 52): (i) data collection, (ii) metrics computation, (iii) archetype classification

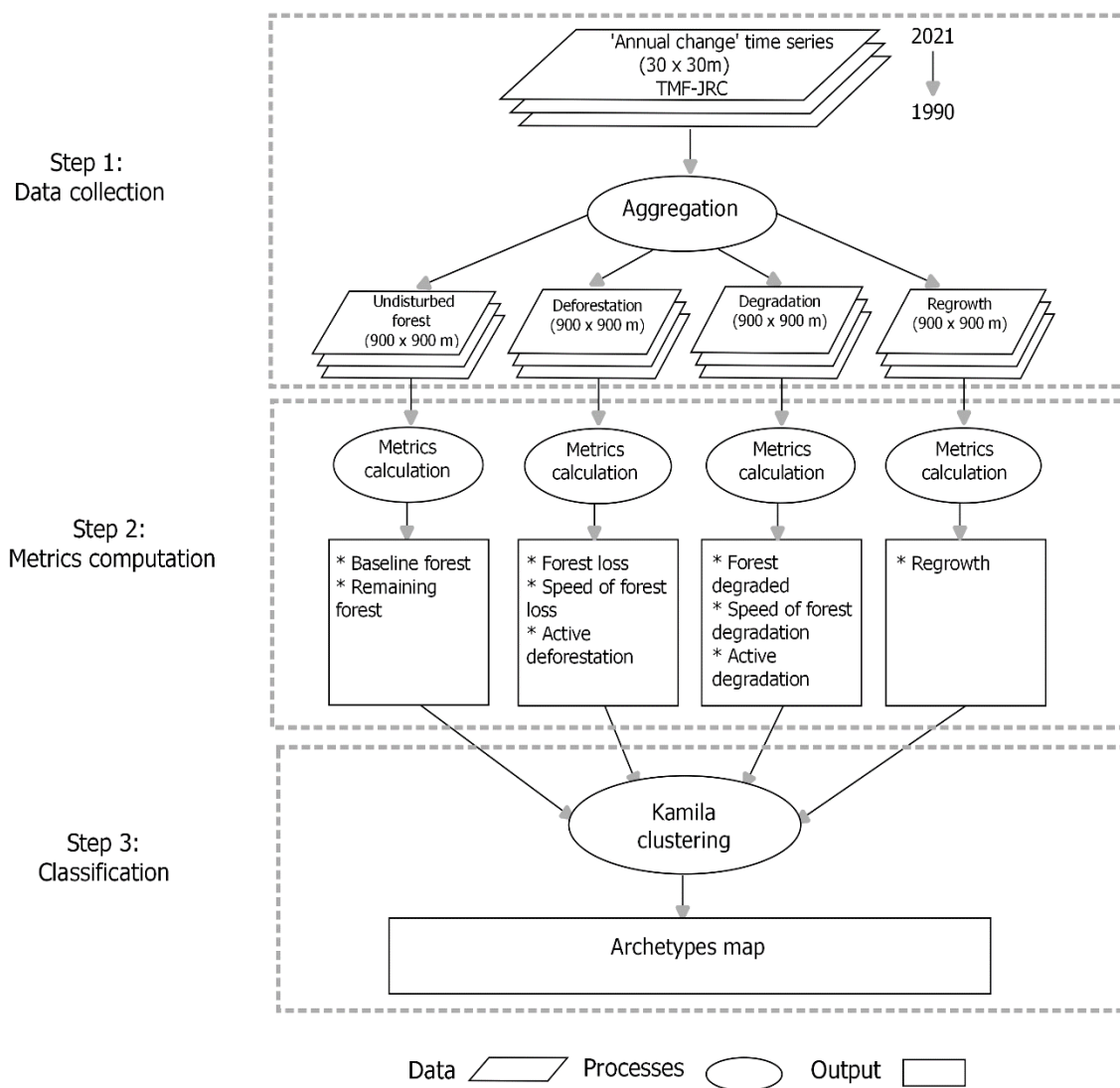


Figure 52: Methodological framework to identify archetypes based on changes in forest cover.

2.2.2.1 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).

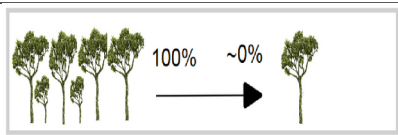
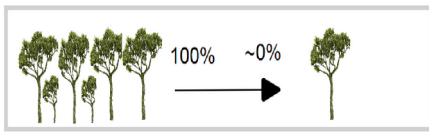
We used the 'Annual change collection' of the Tropical Moist Forest (TMF) dataset developed by the European Commission's Joint Research Centre (EC-JRC), which is based on a 32-year Landsat time series (1990-2021) (Vancutsem et al., 2021). The 32 maps contain information at 30 m resolution on forest extent, 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 observed over the full observation period.

2.2.2.2 Metrics computation

Following Buchadas et al., 2022, we developed a set of nine metrics (Table 5). 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

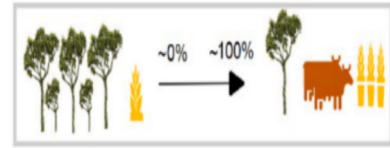
metrics are related to forest degradation (percentage of forest degradation, speed of degradation and activity of degradation). We focused on independent degradation (i.e. logged, burned, logged and burned) as it was defined by Matricardi et al., 2020. One metric is related to forest regrowth (percentage 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 km² cell grid (0.81 km² 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 km² 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).

Table 5: Characteristics of the nine metrics computed in a grid with cells of 0.81 km² (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

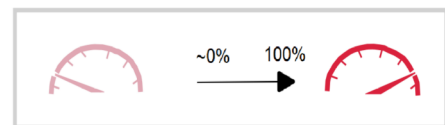
/Baseline forest * 100)
computed for each cell of
the grid



Deforestation

Speed of
forest
loss

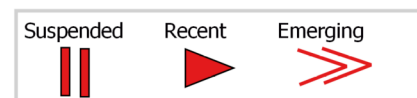
Maximum rate of
deforestation (km²/year)
calculated for the period
1990-2021. For each cell,
the surface area of
annual deforestation was
fitted using a LOESS
regression. The speed of
forest loss is the
maximum value of the
first derivate
(corresponding to the
highest annual velocity of
forest loss). The speed
of forest loss of
deforestation was scaled
as a percentage based
on the highest value in
the 3 sites.



Deforestation

Active
deforest
ation

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

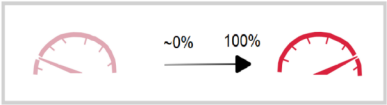
Percentage of forest degraded in 2021 computed for each cell of the grid



Degradation

Speed of forest degradation

The same computation as the speed of forest loss using degradation data



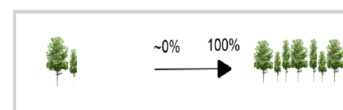
Degradation

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
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2.2.2.3 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).

2.3 Results

2.3.1 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.

Archetype 1 (Fig. 53a) 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. 53b) 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 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'.

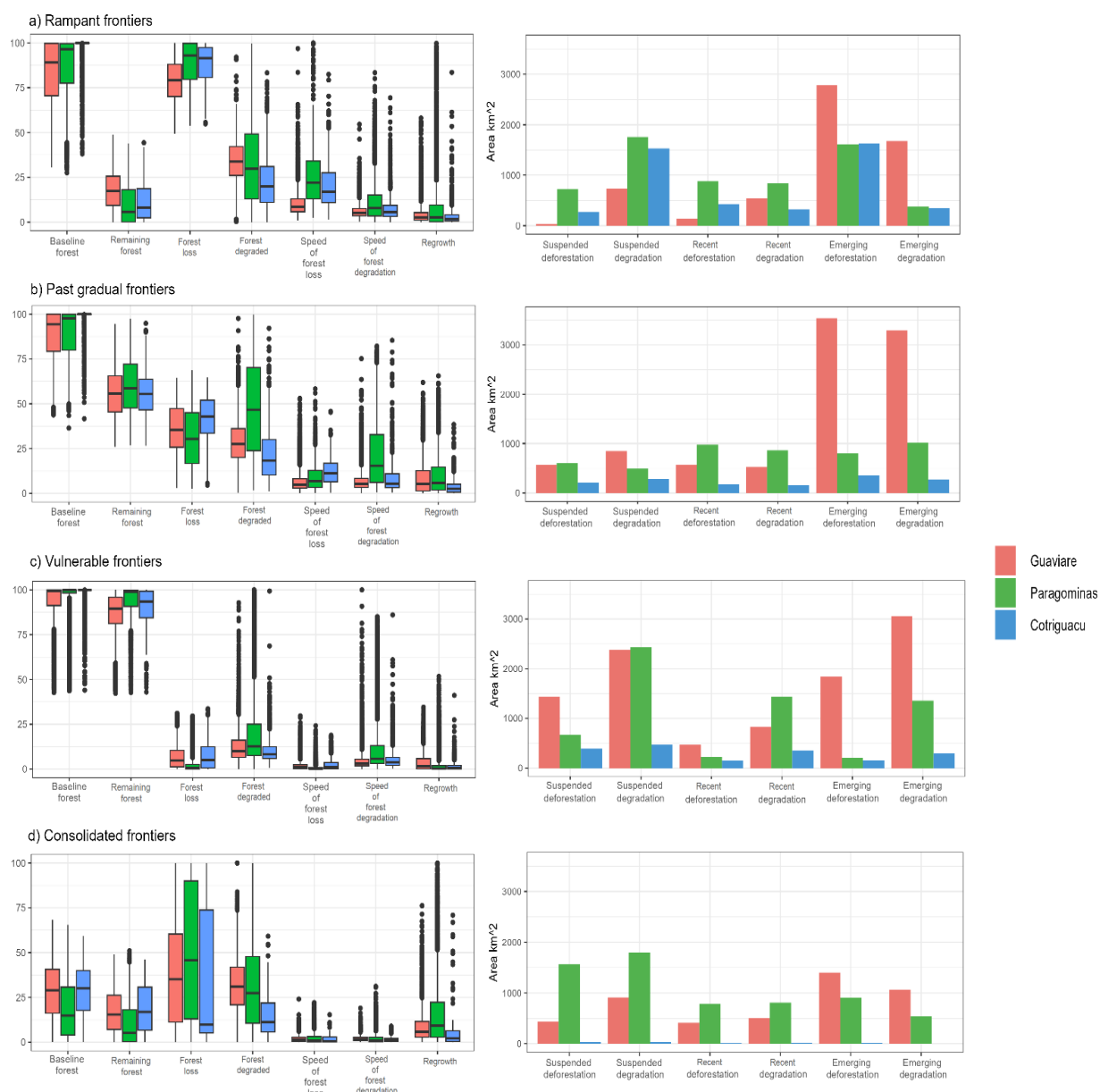


Figure 53: Distribution of the 7 continuous metrics (left) and the 2 categorical metrics (right) related to deforestation, degradation and regrowth for the four archetypes at each study site.

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 km² over the period 2010-2020 (Fig. A1). Deforestation in Paragominas decreased from 2137.1 km² between 1999 and 2009 to 1090.1 km² over the period 2010-2020. Over the same periods, a decreasing trend was also observed in Cotriguaçu, where deforestation fell from 1533.5 km² to 613.9 km² and forest degradation from

435.9 to 238.7 km². In Guaviare, deforestation over the period 1999-2009 was 1289.45 km² and increased to 2 246 km² over the period 2010-2020 whereas forest degradation fell from 1530.18 km² to 1232.26 km². 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 km² and 21.33 km², respectively. In Paragominas, between 2010 and 2015, the annual area of secondary forests was 12.3 km² and increased to 77.0 km² in 2016, 140.3 km² in 2017 and to 252.4 km² in 2018.

2.3.2 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 6). 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 were mainly consolidated frontiers (Fig. 54). 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 6). 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. 54).

Table 6: Area and percentage of the total area represented by each archetype at the three study sites.

	Changes in forest cover				Total area	No changes in forest cover Total area
	Rampant frontiers	Past gradual frontiers	Vulnerable frontiers	Consolidated frontiers		
Guaviare	2 952.3 km ²	4 677.1 km ²	6 813.5 km ²	2 556.6 km ²	16 999.50 km²	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 km²	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 km²	4 733.80 km ²
	25.4%	8.2%	13.7%	0.9%	48.2%	51.9%

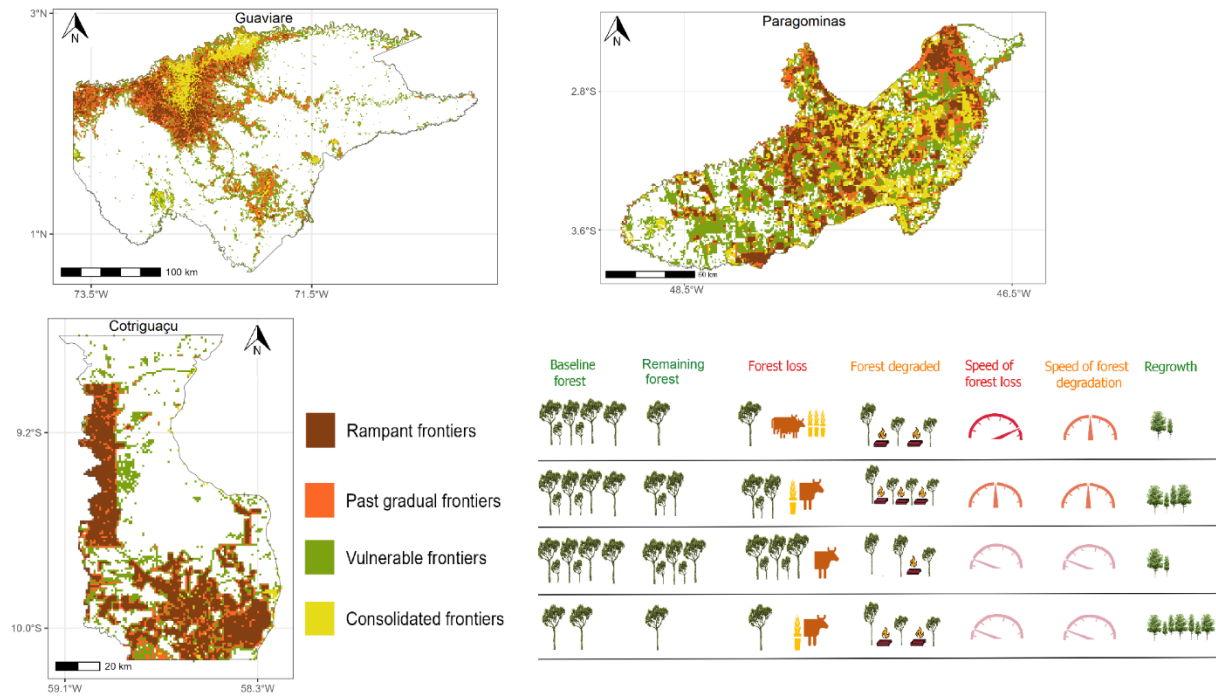


Figure 54: Archetype maps for each study site: a) Guaviare, b) Paragominas and c) Cotriguaçu.

2.3.3 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. 55). 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 7).

Indeed, in Paragominas, degradation occurred in the absence of deforestation in 77% of the vulnerable frontiers (Table 7). 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 km², i.e., 1.3%).

In both Guaviare and Cotriguaçu, the degradation process occurred without deforestation in respectively, 41% and 44% of the vulnerable 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. 55). 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. 55). 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. 55).

Table 7: Area and percentage of active deforestation and active degradation at the three study sites.

Guaviare Area (km ²)						
Deforestation			Degradation		No	Total
		Suspended	Recent	Emerging		
	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 km² (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 km² (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 km² (27%)
Total		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 km² (45%)
Total		2 377.4	823.1 km²	3041.1	571.7	6 813.5

		km ² (34.9%)	(12.1%)	km ² (44.6%)	km ² (8.4%)	km ² (100%)
Paragominas Area (km ²)						
Deforestation	Degradation					
		Suspended	Recent	Emerging	No	Total
	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 km² (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 km² (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 km² (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%)	4 352.0 km² (79.8%)
	Total	2 433.7 km² (44.7%)	1 435.3 km² (26.3%)	1 349.7 km² (24.8%)	231.5 km² (4.2%)	5 450.3 km² (100%)
Cotriguaçu Area (km ²)						
Deforestation	Degradation					
		Suspended	Recent	Emerging	No	Total
	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 km² (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 km² (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 km² (12.4%)
	No	169.70 km ² (13.5%)	207.76 km ² (16.6%)	158.60 km ² (12.7%)	26.96 km ² (2.2%)	563.0 km² (44.9%)
	Total	466.3 km² (37.2%)	350.5 km² (28%)	297.4 km² (23.7%)	138.8 km² (11.1%)	1 252.9 km² (100%)

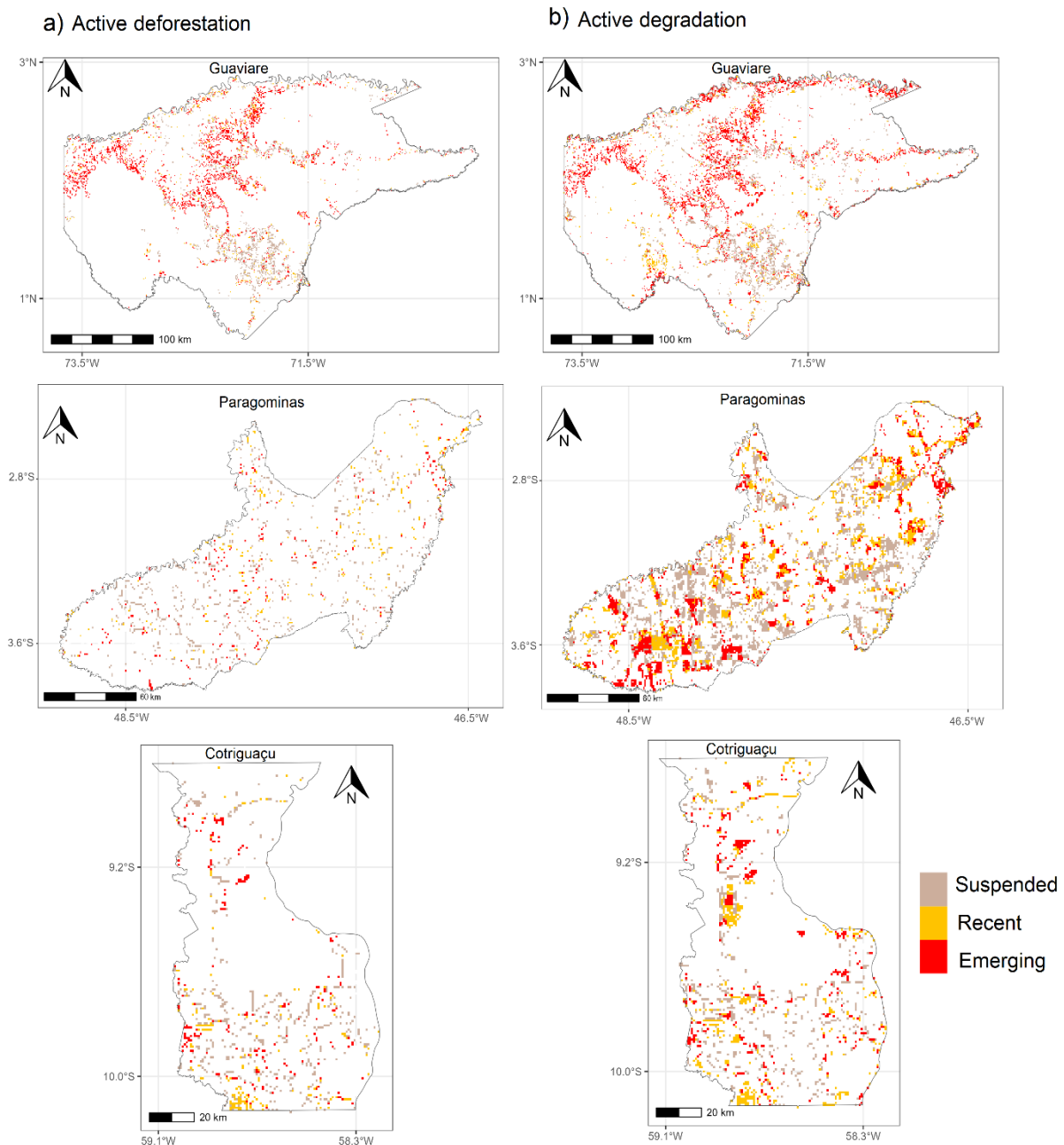


Figure 55: Active deforestation (a) and active degradation (b) in vulnerable frontiers at each study site.

2.3.4 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 km²,

4031.4 km² and 1052.6 km² in Guaviare, Paragominas and Cotriguaçu respectively. To a lesser degree, undisturbed forests were also observed in past gradual frontiers (1549.5 km², 614.8 km², 349.0 km², respectively). Undisturbed forests accounted for only a small area in rampant frontiers (< 277.6 km²) and in consolidated frontiers (< 182.3 km²).

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 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 forest.

2.4.1 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, Thalès 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.

2.4.2 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 (P. Fearnside, 2017; P. M. Fearnside,

2017; 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, accounting for respectively, 337 km² and 308.31 km², (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 6). 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-Céspedes et al., 2021; Murillo-Sandoval et al., 2023, 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 4.4.3). 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.

2.4.3 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 of deforestation (Table 8). 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., 2015, 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.

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.

Table 8: 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) - Urgent Clarification of the land tenure issue, the legal obligation for restoration and land use sustainable intensification and strong control against the use of fire in agricultural and cattle ranching practices
	Illegal	- Strong additionality for PES aimed at forest conservation - Targeting those areas for command-and-control policies against land mafia
Rampant frontiers	Legal	- Strong additionality for PES aimed at restoring forests - Clarifying urgently the land tenure issue, the legal obligation for restoration and land use intensification
	Illegal	- Strong additionality for PES aimed at restoring forests - Clarifying urgently the land tenure issue, the legal obligation for restoration and land use intensification

2.5 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.

CHAPTER 3- ANALYSIS OF THE STRUCTURE OF ARCHETYPES AND DRIVERS OF FOREST COVER CHANGE.

Abstract: The Amazon frontiers face escalating threats from agricultural expansion and associated land-use changes. This study analyzes Amazonian forest cover change between 1991 and 2021 in three areas (Guaviare, Colombia; Paragominas and Cotriguaçu, Brazil) using an integrated set of archetypes for land system trajectory, landscape metrics, fire behavior, and institutional settings. Four archetypes —consolidated, vulnerable, past gradual, and rampant frontiers —were used, capturing specific trends of deforestation, degradation, and regrowth. By merging spatially integrated data (MapBiomas, TMF), transition for land use, fragmentation indicators, and fire behavior were estimated. Results suggest non-converging land-change paths: rampant and consolidated frontiers experienced high pasture expansions accompanied by strong fragmentation, whereas past gradual frontiers experienced slow forest loss but strong degradation and regrowth. Vulnerable frontiers had maintained forests, but with early degradation. Fire-enabled land management and degradation, particularly in the context of the rampant and past gradual frontiers. Institutional settings had a significant impact; the presence of an area for protection helped the Guaviare forests, while the tools for private lands (e.g., Brazil's Rural Environmental Registry) influenced Brazilian outcomes. Transitions between agricultural economic land uses differed between the two countries, with Brazil presenting complex transition modes (e.g., pasture-to-cropland transition) and Colombia exhibiting a direct forest-to-pasture transition. Results suggest the need for the development of individual policies, such as fire management, restoration incentives, and law enforcement, that are responsive to the archetypes. Our findings contribute to improved Amazonian land-use planning and forest conservation by recognizing archetypes as a reusable tool for addressing these problems in complex tropical areas.

3.1. Introduction

The growing global demand for food to sustain the world's population has driven the expansion of agricultural frontiers (Foley et al., 2011). In the Amazon

basin, particularly within the arc of deforestation, land use changes are driven by interrelated socio-ecological dynamics (Kalamandeen et al., 2018; Kruid et al., 2021). Similar processes are observed in regions characterized by intensive agricultural activity (Corgne et al., 2014, 2003). Different drivers of deforestation, forest degradation and regeneration processes interact to reshape these forest landscapes (Lambin et al., 2003; Lapola et al., 2023).

The increase of anthropogenic pressures and the acceleration of land use change threaten the delivery of key ecosystem services and contribute to increasing landscape fragmentation (Laurance et al., 2001; Rosa et al., 2017). Changes in these landscapes due to deforestation and forest degradation have multiple consequences: carbon loss (Aragão et al., 2014), biodiversity decline due to habitat loss and fragmentation (Chaves and Arango, 1998; Terborgh, 1989), altered climate regimes (Laurance et al., 2014), increased landscape fragmentation (Hansen et al., 2020), reduced ecological connectivity (Murillo-Sandoval et al., 2022), structural changes in forests due to logging and fire (Bourgoin et al., 2024), greater vulnerability to extreme events such as El Niño (e.g. 1998, 2005, 2010, 2015; Cai et al., 2014), and erosion of ecosystem services (DeFries et al., 2004; Foley et al., 2007).

Recent research has underscored the importance of adopting multi-scalar perspectives, innovative methodological approaches, and refined metrics to grasp the complexity of forest cover change and its underlying drivers (Oberlack et al., 2016; Sietz, 2014; Sietz et al., 2019). Among these emerging approaches, the use of land system trajectory archetypes has proven particularly valuable in elucidating patterns of human-environment interactions. These archetypes reflect the trajectories of land use change (Briceño et al., 2025; Buchadas et al., 2022; Eisenack et al., 2021, 2019). The archetype diversity reflects the complex and context-specific interplay between environmental conditions and socio-economic drivers.

However, the spatiotemporal characterization of land-use transitions within archetypes remains insufficiently explored. Changes over time were conceptually framed by Foley et al. (2005) through a sequence of five stages of land transformation—ranging from undisturbed forest to territorial reclamation, subsistence agriculture, gradual intensification, and eventually intensive land use—each shaped by distinct regional, historical, social, and economic contexts (DeFries et al., 2004; Tolessa et al., 2016).

At various spatial scales, fragmentation and forest connectivity have also been analyzed to study the impact of land use changes on biodiversity. Globally, studies have assessed the extent of fragmentation in tropical forests (Fischer et al., 2021) and the effect of edge effects on forest structure (Bourgoin et al., 2024). At the national scale, the connectivity of forests has also been evaluated (Murillo-Sandoval et al., 2022).

In the context of tropical forests, however, most assessments of fragmentation and structural changes have historically focused on deforestation alone (Alves et al., 2021; Haddad et al., 2015; Taubert et al., 2018). Deforestation, defined as the permanent conversion of forest cover to other land uses, has been the target of numerous policy measures and institutional frameworks aimed at reducing its rate across Amazonian countries (Arima et al., 2014). However, two other processes in tropical forests - forest degradation and regeneration- are increasingly recognized as critical components of forest landscape dynamics (Broadbent et al., 2008). Recently, forest degradation in the Amazon has been reported to have reached record levels from 2001-2018, exceeding deforestation (Lapola et al., 2023; Vancutsem et al., 2021). The important contribution of forest degradation to carbon stocks and ecosystem services has also been assessed (Aragão et al., 2018; Berenguer et al., 2021). Secondary forests in the Amazon region also occupy important areas (Nunes et al., 2020),

and secondary forest areas are important for conservation, restoration, and carbon storage (Elias et al., 2020; Heinrich et al., 2023; Perz et al., 2010).

The overarching objective of the research was to integrate the trajectory archetype approach (Briceño et al., 2025) with the landscape metrics approach, while also examining fire dynamics and the legal and institutional framework to better understand their influence on the spatial distribution of the forest archetypes. To achieve this, we collected data across three subnational jurisdictions within the Amazon Basin, and structured the analysis around three specific objectives:

1. To analyse the spatiotemporal dynamics of the composition and configuration of land system archetypes from 1991 to 2021 across the three selected jurisdictions;
2. To quantify the temporal distribution of fire events within the archetypes;
3. To assess the influence of the legal and institutional framework on the spatial distribution of archetypes at the subnational scale.

We address the following research questions:

1. What is the relationship between land use transformation processes and changes in the structure of archetypes (composition and configuration)?
2. What is the role of fire in shaping the dynamics of each archetype?
3. How are different legal and institutional framework and land use regulations associated with each archetype?

The findings of this study will inform the identification of context-specific priorities for forest management, tailored to the characteristics of each jurisdiction.

3.2 Materials and methods

3.2.1 Study sites

Our study focused on three Amazonian regions (Fig. 56): two municipalities in Brazil (Paragominas and Cotriguaçu) and one department in Colombia

(Guaviare). In an effort to transition toward a development model that harmonizes social progress with biodiversity conservation, these regions have committed to implementing regulations aimed at reducing deforestation. The key geographical and socioeconomic characteristics of each area are listed below.

-The Department of Guaviare in Colombia has an area of 53 460 km² and a population density of approximately 1.55 persons per km² (DANE, 2018). The colonization of this region began approximately in 1960 (Arcila et al., 1999). San José de Guaviare, the department's capital, and its surrounding northern areas are home to most of the population. Since 1982, Guaviare has lost 3,011 km² of forest cover, representing 5.4% of its total area. Between 1982 and 2020, the highest concentration of deforested areas is located in the southern and northern parts of the department (Fig. 56).

-The municipality of Paragominas, located in the state of Para in northern Brazil, covers an area of 19 342 km² and has a population density of approximately 5,45 people per km² (IBGE, 2023). The construction of the Belém-Brasília highway, which began in 1960, marked the start of colonization in the region (Uhl and Guimaraes, 1989). Between the 1960s and 2005, Paragominas experienced high rates of deforestation and environmental degradation. Livestock farming has been the primary driver of deforestation, with large-scale cattle ranching prevalent until the 2010s, when fire was increasingly used to prevent shrub species from overtaking the grasslands (Carvalho et al., 2020).

-The municipality of Cotriguaçu, located in the state of Mato Grosso in Central-West Brazil, has a land area of 9 124 km² and a population density of approximately 1.21 inhabitants per km² (IBGE, 2023). Of the total area, 18.5% is indigenous land known as "Escondido," and 14.7% is part of the Juruena National Park. The Rikbaktsa tribe, an indigenous group, used to live in Cotriguaçu (Sills et al., 2014). The first wave of immigrants from the southern Brazilian state of Paraná arrived in Cotriguaçu in 1984. In 1991, Cotriguaçu transitioned from a district to a municipality, and four rural reform settlements 'Nova Cotriguaçu,' 'Juruena,' and 'Sonho Meu' were established. Cattle ranching

and timber exploitation have been the main economic activities in the municipality.

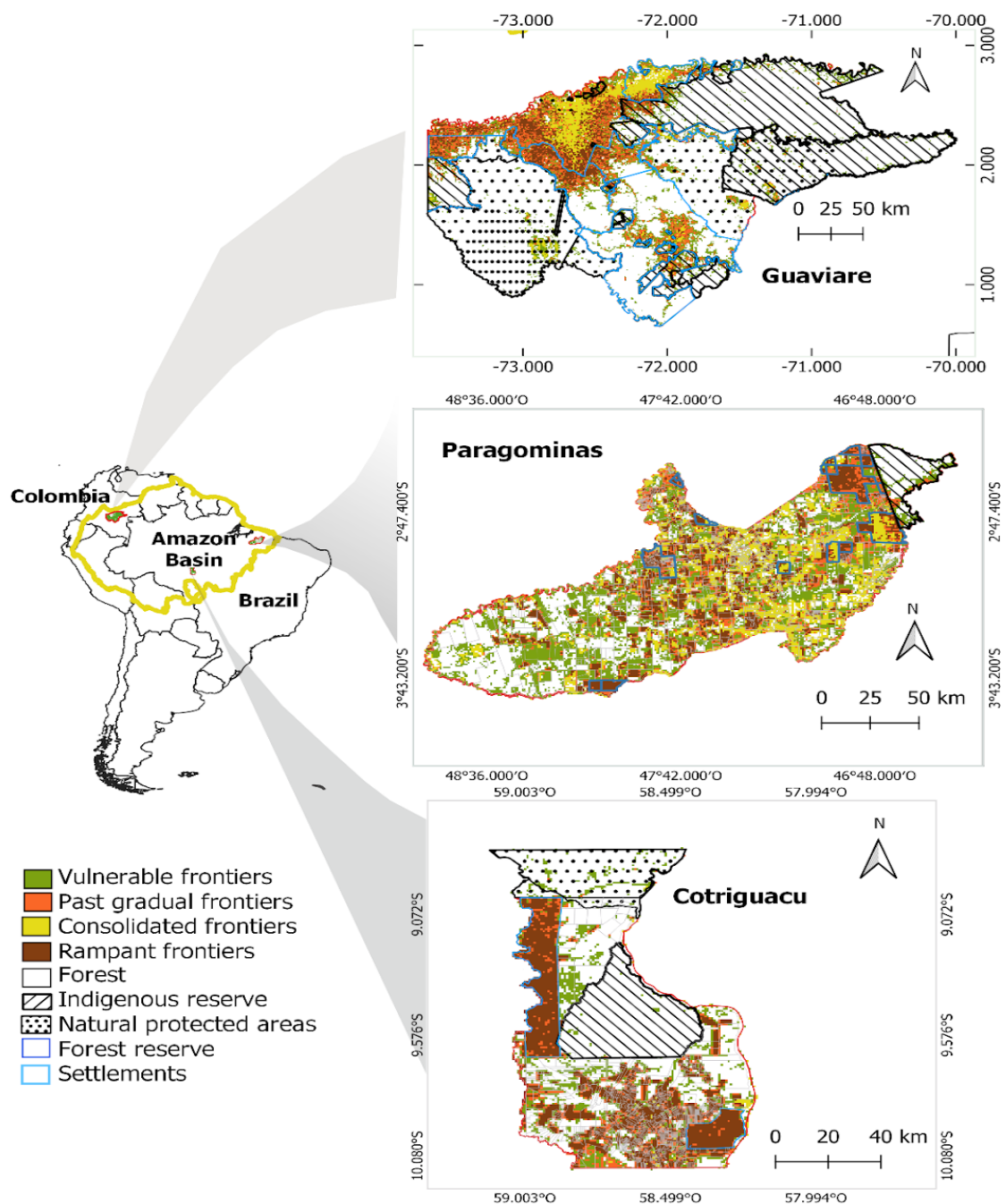


Figure 56: Locations of the three study sites (the department of Guaviare in Colombia, and the municipalities of Cotriguaçu and Paragominas in Brazil), archetype maps (from Briceno et al. 2025) and administrative limits.

3.2.2 Datasets

3.2.2.1 Archetypes data

We used archetype maps for the three study sites obtained from Briceño et al. (2025). Archetypes are defined as forest cover changes or frontiers types that are characterized by a similar set of metrics related to the three processes of deforestation, forest degradation and regeneration. These archetypes represent unique combinations of the full range of forest cover patterns and changes. Four archetypes were identified: consolidated frontiers, vulnerable frontiers, past gradual frontiers and rampant frontiers (Fig. 56). Consolidated frontiers are areas that have undergone high levels of deforestation over an extended period, leading to a stable land-use transition. Vulnerable frontiers are regions that still maintain significant forest cover but show signs of past or ongoing deforestation and degradation. Past gradual frontiers and rampant frontiers are characterized by moderate to high levels of deforestation, often accompanied by considerable forest degradation. Archetypes were calculated only for areas where deforestation, degradation, and regeneration were observed, each exceeding 5% by cell grid. Ultimately, each pixel was assigned to one of the five categories: four archetypes or no forest cover change; for further details on the development of these archetypes, refer to Briceño et al. (2025).

3.2.2.2 Spatiotemporal land use data set from TMF and MapBiomass integration

The assessment of spatiotemporal dynamics in land use in the three study sites was based on the integration Land use maps provided by the MapBiomass project (MapBiomass, 2024) and the Tropical Moist Forest (TMF) product from the European Commission's Joint Research Centre (EC-JRC). To facilitate temporal analysis, we constructed a new time series combining both datasets for the period 1991 to 2021, but selected only 7 dates (1991, 1996, 2001, 2006, 2011, 2016, and 2021) to visualize our results. The methodological sequence was presented in the chapter 1.

3.2.2.3 Land use composition and land use transition

Using this dataset, we quantified the temporal evolution of the percentage of land use (LU) for each archetype at selected time points (1991, 1996, 2001, 2006, 2011, 2016, 2021). This was achieved using the PLAND function from the 'landscapemetrics' package (Hesselbarth et al., 2019) in R (R Core Team, 2013), which calculates the proportional area of each LU class.

LU transitions were further analyzed using Sankey diagrams derived from transition matrices. In these diagrams, the total area occupied by each LU category in years 1991, 2005 and 2021 (only 3 years are represented for figure clarity) is represented by stacked vertical bars, with the height of each bar indicating the relative share of each LU type within the study areas. These years serve as critical snapshots that capture the baseline condition, a major intermediate point, and the most recent state. Transition flows between bars depict areas undergoing LU change or remaining stable. The thickness of each flow is proportional to the total area corresponding to that transition or unchanged LU class. The Sankey diagrams were computed using 'crosstab' function from the 'terra' package (Hijmans, 2020) in R version 4.1.2.

3.2.2.4 Forest configuration metrics

We also analysed the landscape configuration of each archetype by computing various landscape metrics related to patch size, shape, and spatial arrangement, with a focus on forest fragmentation. Considering only the forest category, which includes both undisturbed and degraded forest classes, we thus calculated four configuration metrics (Armenteras et al., 2013; Arroyo-Rodríguez et al., 2017) - edge density, largest patch index, mean patch area, and number of patches - and a fifth additional composition metric which is the percentage of forested land (see Table 9 for details).

Following Briceno et al. (2025) the calculation of landscape metrics was performed at a approximately 1 km² cell grid (0.81 km² 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 km² cell was selected because it captures 99% of the variability of the sizes of both forested and deforested patches.

Table 9: Forest (merged undisturbed and degraded forest classes) metrics calculated at the cell scale. Source: McGarigal and Marks (1995).

Metric name	Formula
Edge density	$\frac{\sum_{j=1}^n e_j}{A}$ Where e_j is the edge length of patch j (m) and A is the total cell area (ha)
Largest patch index	$\frac{\max_{j=1}^n (a_j)}{A} * 100$ Where a_j is the area of patch j (m ²) and A is the total cell area (m ²)
Mean patch area	$\text{mean}(a_j)$ Where a_j is the area of each patch j (ha)
Number of patches	n is the number of patches in the cell area
Percentage of forested land	$\frac{\sum_{j=1}^n a_j^{core}}{A} * 100$ Where a_j^{core} is the area of patch j (m ²) and A is the total cell area (m ²)

Following Briceño et al. 2025 the calculation of landscape metrics was performed at a spatial scale of 1 km². The cell size was established in relation to the size distribution of forest patches and deforested areas. A 1 km² cell was selected because it captures 99% of the variability of the sizes of both forested and deforested patches.

3.2.2.5 Fire products

We used two complementary datasets to analyze fire occurrences and temporal patterns in each archetype: The Global Forest Loss Due to Fire (GLAD-Fire) product from the University of Maryland (GLAD-Fire dataset), covering the

period from 2001 to 2019, with a spatial resolution of 30 meters (Tyukavina et al., 2022). and The Burned area maps from MODIS. The data, available at <https://doi.org/10.5067/MODIS/MCD64A1.061>, is presented in more details in Chapter 1.

3.2.2.6 Administrative and legal framework data

We analysed the distribution of forest landscape archetypes across different legal and institutional frameworks in the Colombian and Brazilian Amazon. Legal and institutional frameworks refer to the suite of laws, regulations, policies, and governance mechanisms that dictate the use, management, and conservation of natural resources and land. To conduct this analysis, we utilized official administrative boundary data, including municipal borders for the states of Pará and Mato Grosso in Brazil, obtained from the Brazilian Institute of Geography and Statistics (IBGE) at a scale of 1:250,000, and geographic data for the Department of Guaviare in Colombia from the SIAC national portal. It is presented in more details in Chapter 1.

3.3 Results

3.3.1 Spatio-temporal dynamic of the archetypes structure

The spatiotemporal dynamics of each archetype were characterized through analyses of landscape composition, land use transitions, and spatial configuration. We examined changes in land use composition and configuration between 1991 and 2021 for each archetype across the three study areas.

3.3.1.1 Composition by archetypes

Within the consolidated frontier regions, pasture remained the predominant land use throughout the study period across all three territories (Fig. 57). In Guaviare, pasture exhibited a moderate expansion, increasing from 42% to 63% of the archetype between 1991 and 2021. In the Brazilian sites, pasture areas showed a slight increase until 2006, followed by a subsequent decline most notably in Paragominas, where pasture coverage decreased from 75% in 2011 to 50% in 2021. Undisturbed forest cover accounted for less than 35% of this archetype across all three sites at the beginning of the study period and exhibited a continuous decline, reaching 10% in Guaviare, 18% in Cotriguaçu,

and 5% in Paragominas by 2021. Concurrently, areas of forest regrowth emerged, particularly in the Brazilian sites (Fig. 56) alongside the emergence of soybean cultivation in Paragominas (Fig. 58).

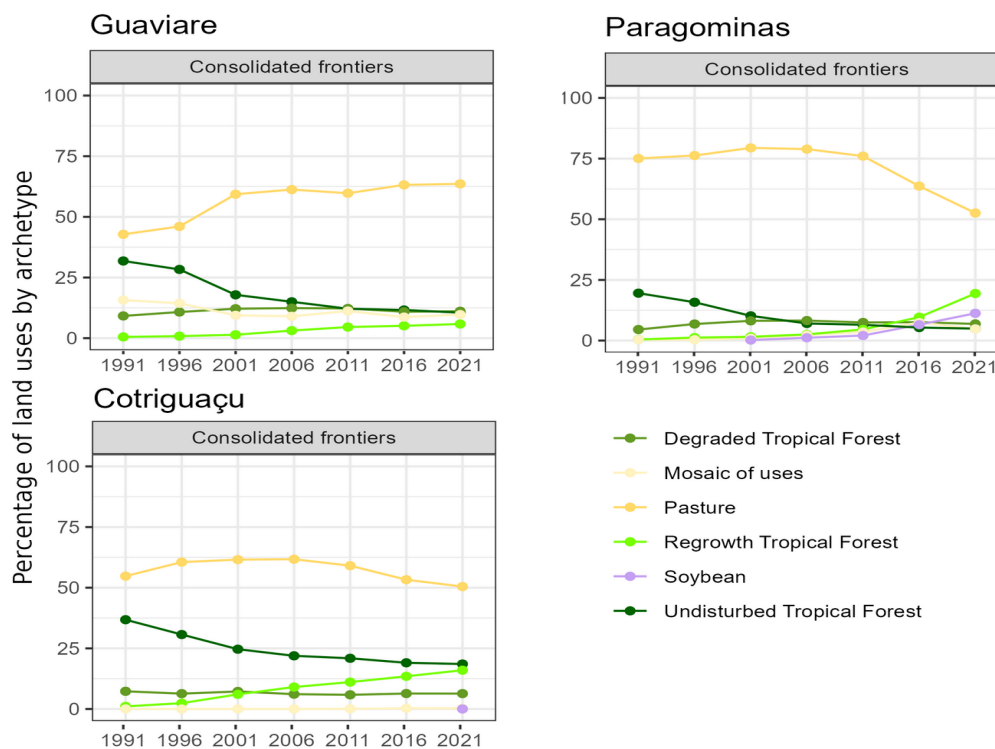


Figure 57: Composition of land uses within the consolidated frontier regions across the three study sites during the period from 1991 to 2021.

Rampant frontier regions experienced a marked decline in undisturbed forest cover across all three sites, with forest areas accounting for less than 9% of this archetype by the end of the study period. This decline was accompanied by a substantial expansion of pasture in Guaviare and Cotriguaçu. In Paragominas, pasture area also increased initially, reaching a peak around 2006, after which it stabilized and subsequently declined. A similar dynamic was observed in Paragominas for degraded forests, albeit to a much lesser extent, characterized by an initial increase, a peak between 2001 and 2006, and a gradual decline thereafter. Similar to the consolidated frontier, soybean cultivation in the rampant frontier of Paragominas began to expand from 2006 onward (Fig. 58).

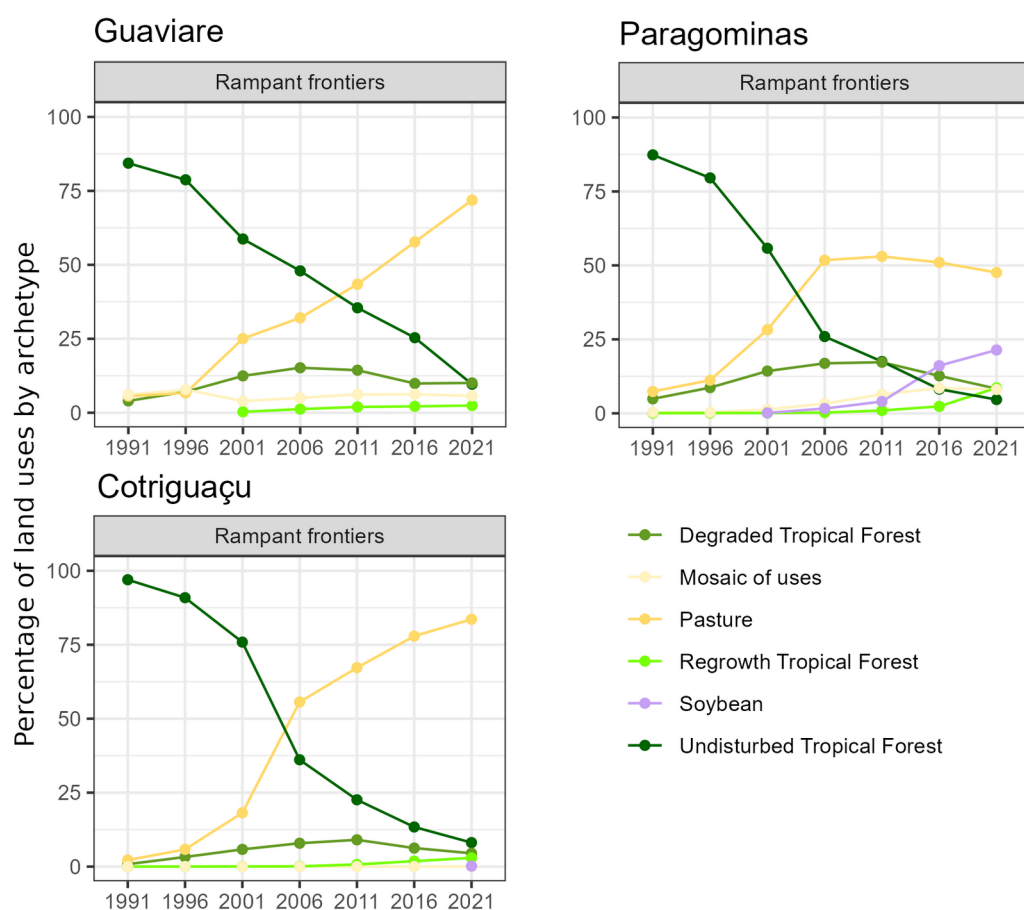


Figure 58: Composition of land uses within the rampant frontiers regions across the three study sites during the period from 1991 to 2021.

In the past gradual frontier regions, undisturbed forest cover also underwent a significant decline, similar to the rampant frontiers, though the rate of decline was less abrupt. Pasture areas expanded in both Guaviare and Cotriguaçu between 1991 and 2021, but did not exceed 25% and 33% of the archetype, respectively. In contrast, Paragominas exhibited an increase in pasture cover followed by a period of stability between 2006 and 2021, and a subsequent decline thereafter. In Guaviare and Cotriguaçu, degraded forest area exhibited a continuous increase throughout the study period. In contrast, Paragominas experienced a more rapid expansion of degraded forests, peaking at 39% in 2016, followed by a stabilization phase (Fig. 59).

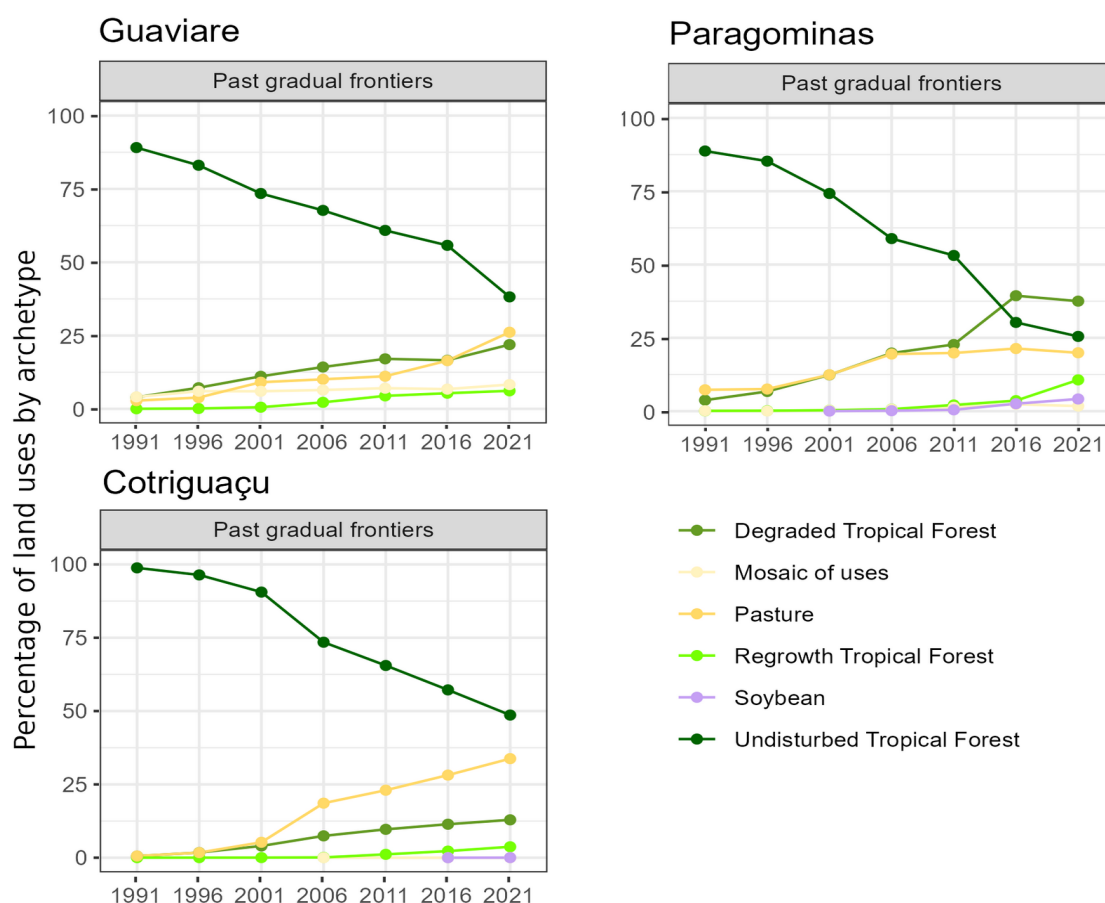


Figure 59: Composition of land uses within the past gradual frontiers regions across the three study sites during the period from 1991 to 2021.

Land use dynamics in the vulnerable frontiers were less pronounced compared to the other three archetypes. These regions remained predominantly forested, with forest cover showing a slight decline across all three study sites over the entire study period. In contrast, degraded forests exhibited an opposing trend, with a gradual and continuous increase (Fig. 60).

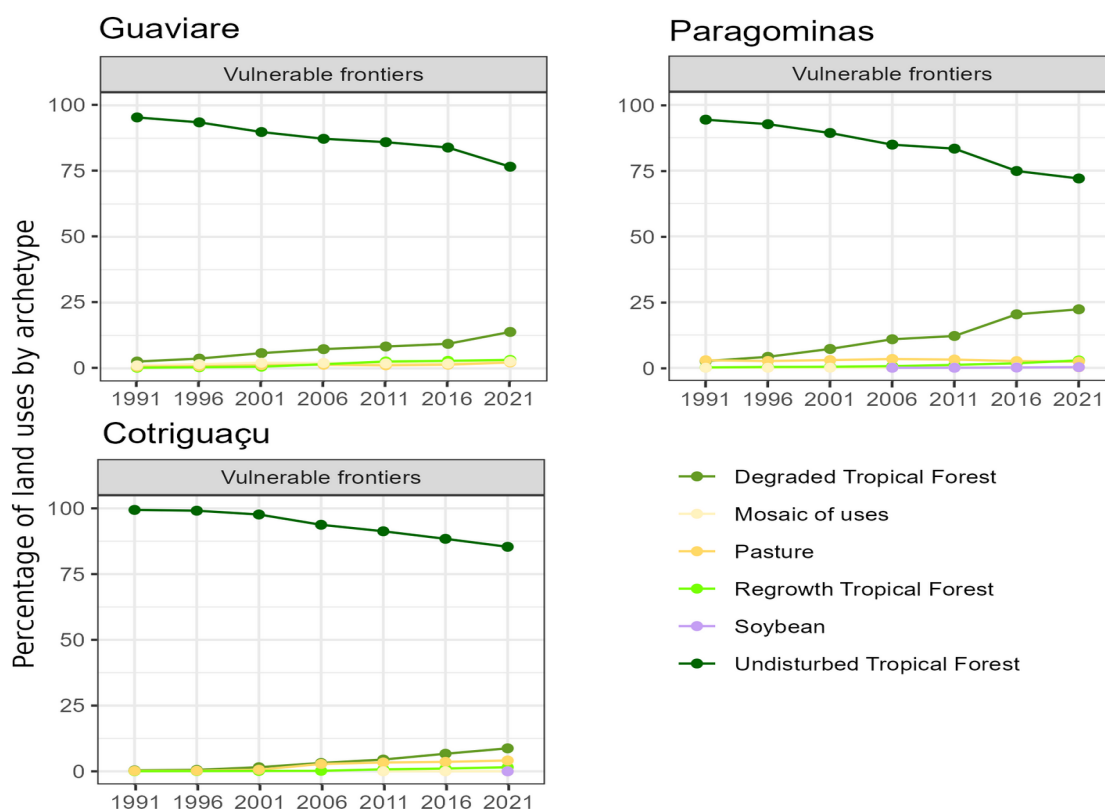


Figure 60: Composition of land uses within the vulnerable frontiers regions across the three study sites during the period from 1991 to 2021.

The land use composition within each archetype reveals distinct patterns of forest transformation and land use dynamics. In the consolidated frontiers, pastureland emerged as the dominant land use between 1991 and 2021, reflecting longstanding deforestation and conversion to pasture. Rampant frontiers experienced high rates of deforestation, while past gradual frontiers exhibited a more moderate decline, with changes primarily associated with the emergence of degraded forests. Agricultural expansion, particularly in Paragominas, was most prominent in archetypes with the lowest percentage of undisturbed forest cover (consolidated and rampant frontiers). Finally, vulnerable frontiers maintained the highest proportion of undisturbed forest across all three study sites, with minimal changes in other land use types. However, this stability was accompanied by early signs of degradation in certain regions, particularly in Paragominas, indicating latent pressures on undisturbed forests.

3.3.1.2 Land use transition by archetype

In the consolidated archetypes, a high percentage of the majority of pasture areas observed in 2021 were established prior to 1991 (Fig. 61). The expansion of pastureland up to 2005 was primarily driven by the deforestation of undisturbed forests in Paragominas, Cotriguaçu, and Guaviare. In the Colombian site, this increase was also linked to the transformation of a mosaic of land uses. After 2005, the modest further increase in pasture areas primarily resulted from the conversion of degraded and undisturbed forests in Guaviare. In the Brazilian sites, pasture area began to decrease post-2005 due to land abandonment for forest regrowth and conversion to agricultural uses in Paragominas only. Between 2005 and 2021, forest cover area, including all forest types, extended in Paragominas (from 476.6 to 1 022.1 km²) and Cotriguaçu (from 15.5 to 21.2 km²) but with radical changes in forest types (less undisturbed forest and more degraded and secondary forests). These are the only two cases of forest cover area increase across all archetypes and all periods.

Within the vulnerable frontier, the significant transition across all three sites is forest degradation of undisturbed forests (Fig. 62). In Guaviare, the conversion of undisturbed forests to degraded forests remained stable between the periods 1991-2005 and 2005-2021, whereas in Paragominas and Cotriguaçu, the conversion is much higher in the 2005-2021 period, increasing from 377.5 km² to 636.7 km² and from 32.4 km² to 112.1 km², respectively.

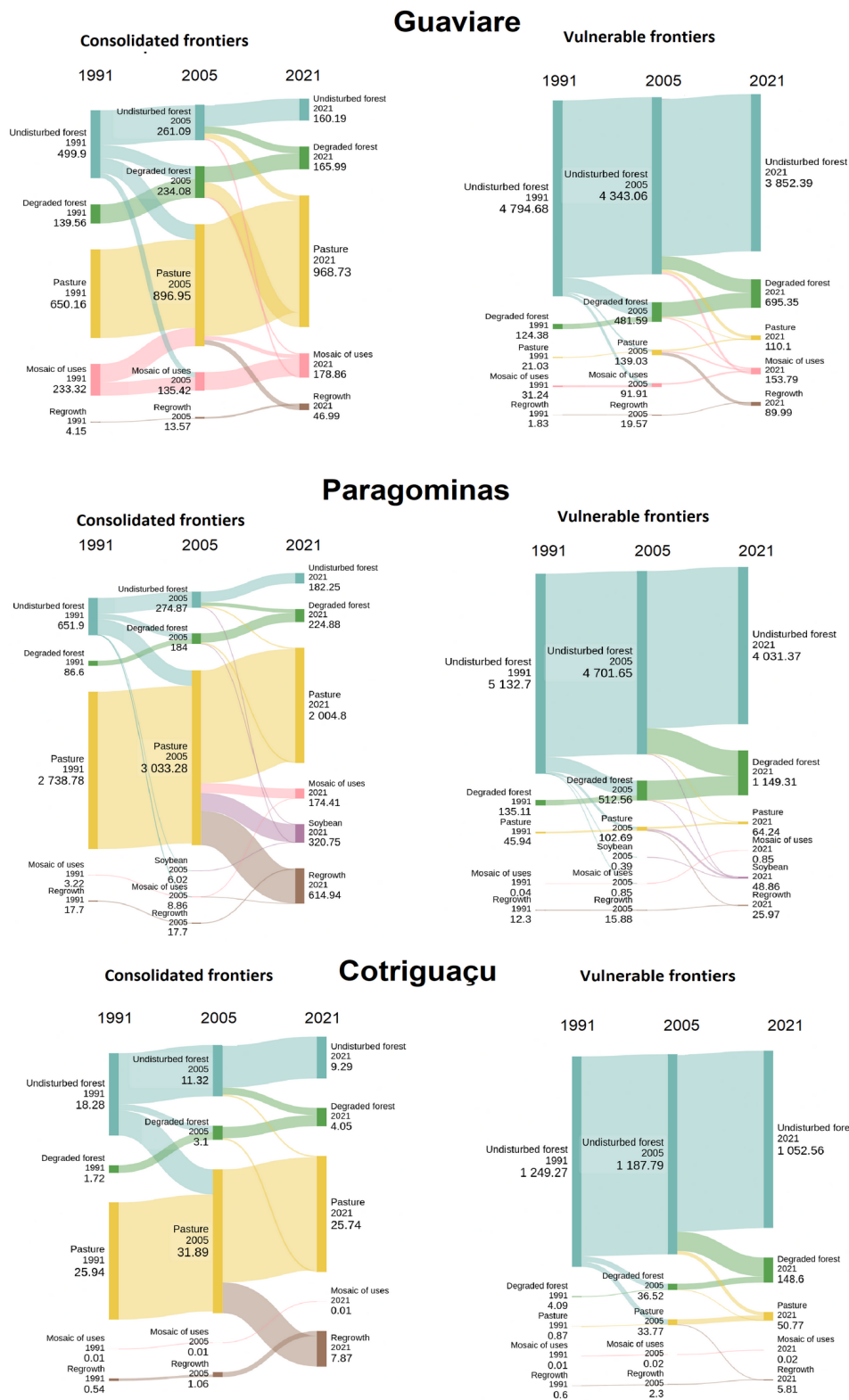


Figure 61: Sankey diagram illustrating land-use transitions (in km²) across three time points 1991, 2005, and 2021 in consolidated and vulnerable frontier regions within the study sites of Guaviare, Paragominas, and Cotriguaçu. The diagram highlights changes among six major land-use categories.

Within the rampant frontier archetype, undisturbed forests were supplanted by pastures and suffered significant degradation. These trends were consistent across both time periods and all three study sites. In Paragominas, although the area designated as pastureland remained stable from 2005 to 2021, new pastures were established at the expense of forests primarily undisturbed, but also degraded while some pastures were converted into soybean cultivation areas and mosaics of uses, or were abandoned to allow forest regrowth. Notably, almost half of the expansion in soybean cultivation (Fig. 62) occurred at the expense of both undisturbed and degraded forests. This archetype is characterized by high dynamism, having undergone substantial land use changes that originated from extensive areas of undisturbed forest.

In the past gradual frontiers, land-use transitions in undisturbed forests mirrored those observed in rampant frontier areas namely, the replacement of primary forests by pastures and the onset of forest degradation (Fig. 62). However, during the period 2005–2021, forest degradation emerged as a more significant driver of change than direct conversion to pastures, with notably high levels of degradation recorded in Paragominas (769.72 km²). In both Guaviare and Cotriguaçu, pasture expansion post-2005 occurred predominantly at the expense of undisturbed forests, with limited conversion from already degraded areas. Forest regrowth between 2005 and 2021 was primarily associated with the abandonment of pastures in the Brazilian sites, while in Guaviare, regrowth also occurred within a mosaic of land uses and in areas of older secondary forest regeneration.

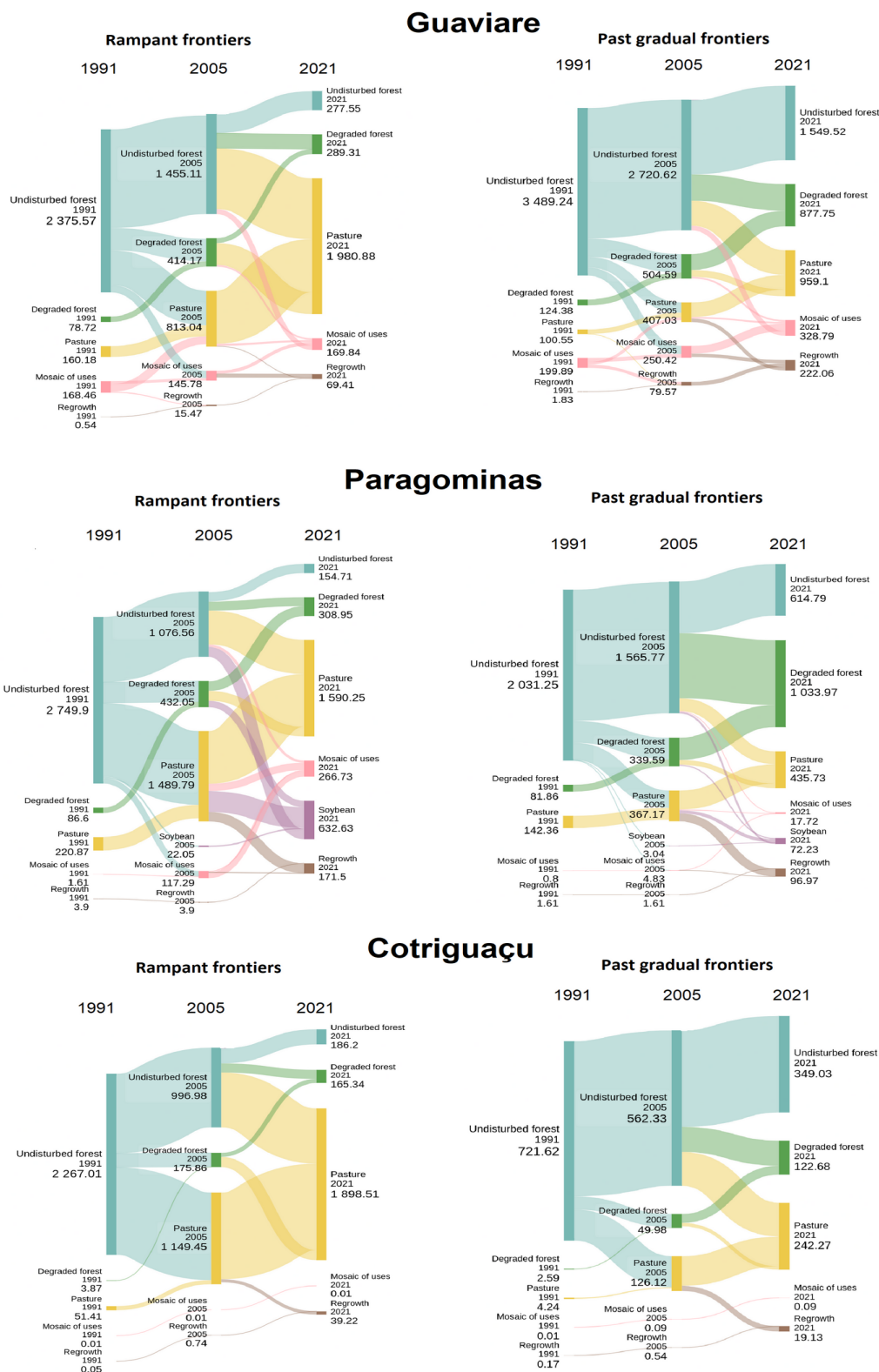


Figure 62: Sankey diagram illustrating land-use transitions (in km²) across three time points 1991, 2005, and 2021 in consolidated and vulnerable frontier regions within the study sites of Guaviare, Paragominas, and Cotriguaçu. The

diagram highlights changes among six major land-use categories providing a comparative view of landscape dynamics over time in each frontier context.

3.3.1.3 Configuration of forest patch in the archetypes

The landscape metrics calculated for the archetypes reflect their level of fragmentation (Fig. 63 ; Appendix B and C for complementary results). Consolidated archetypes exhibited highly fragmented structures, with edge density ranging between 25.38 and 60.45 m/ha, low mean patch size (< 20 ha), and a relatively high number of patches.

Vulnerable archetypes were not yet significantly fragmented, although on the Guaviare site, metrics such as edge density, largest patch index, and mean patch area show high variability.

Finally, the past gradual frontiers and rampant frontiers archetypes showed an increase in fragmentation between 1991 and 2021, marked by rising edge density (from ~20 to ~50), decreasing largest patch index (from ~100 to ~50) and mean patch area (from ~75 to ~20), and an increasing number of patches (from ~0 to ~5). We notice that the metrics for the rampant frontiers in 2021 were quite similar to those of the consolidated frontiers traducing a high level of fragmentation.

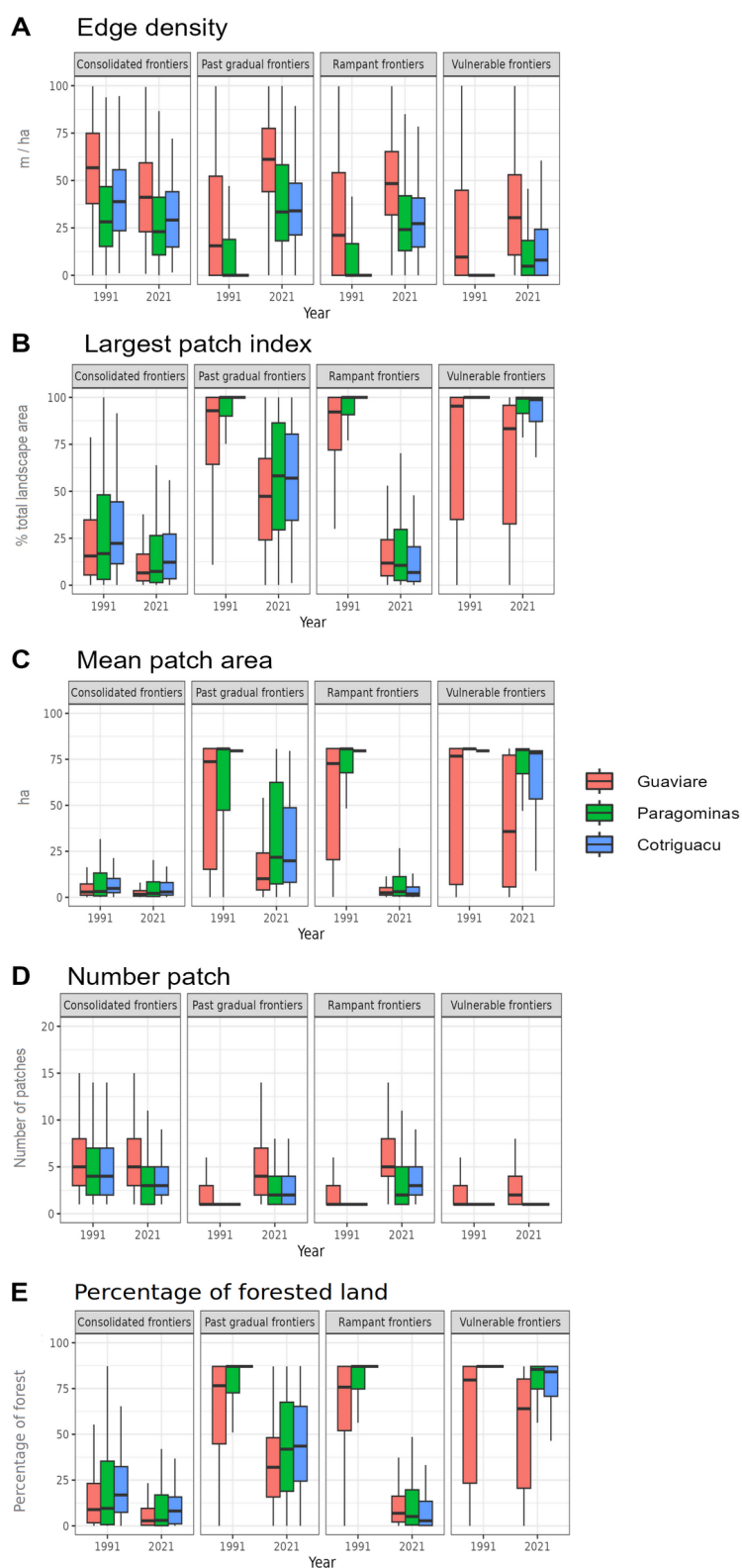


Figure 63: Distribution of the landscape metrics applied to forest (undisturbed and degraded forest) patches within the consolidated frontiers, past gradual frontiers, rampant frontiers and vulnerable frontiers in the three study sites and for two periods. A) Edge density; B) Largest patch index; C) Mean patch area; D) Number of patches; and E) Percentage of forested land.

3.3.2 Fire dynamics

3.3.2.1 *Dynamic of the forest cover loss due to fire and burned area, by archetype*

The archetypes with the highest burned area estimated by Glad Fire are the past-gradual and rampant frontiers for Guaviare, and the rampant frontiers for Cotriguaçu (Fig. 64A). In these two sites, the annual estimated burned area is low, very rarely over 5 km². In Guaviare the year with the highest area burned is 2018. In Cotriguaçu, two peaks of burned area were recorded in 2006 and 2017. Distribution of annual area in Paragominas shows a very different pattern. The burned forest area by archetype in Paragominas showed very low values during the period from 2001 to 2021, with the exception of 2016, when the highest values were recorded in the past gradual frontiers (437 km²) and vulnerable frontiers (357 km²), followed by rampant frontiers (159 km²) and consolidated frontiers (42 km²).

The archetypes with the highest burned area estimated by Modis Fire are the rampant frontiers for all three sites, followed by consolidated frontiers in Guaviare and Paragominas (Fig. 64B). In Cotriguaçu, estimated area by Modis Fire are low in the three others archetypes. Two peaks were observed in 2007 and 2018 in Guaviare, one in Paragominas in 2015. During these peaks, annual values exceed 400 km². Two peaks are also recorded in Cotriguaçu, in 2005-2006 (209 km² and 271 km²) and 2015-2017 (204 km² and 181 km²).

The apparent shift between 2015 and 2016 in the Glad-Fire and MODIS-Fire datasets is due to differences in their temporal data registration methods. MODIS-Fire detects active fires and burned areas on a monthly basis, allowing it to capture events as they occur. In contrast, Glad-Fire uses annual Landsat imagery to map forest loss caused by fire, assigning the loss to the year in which the change is detected. Consequently, large fire events that occur late in the calendar year such as the major fire in Paragominas in December 2015 are registered by Glad-Fire in the subsequent year, in this case, 2016.

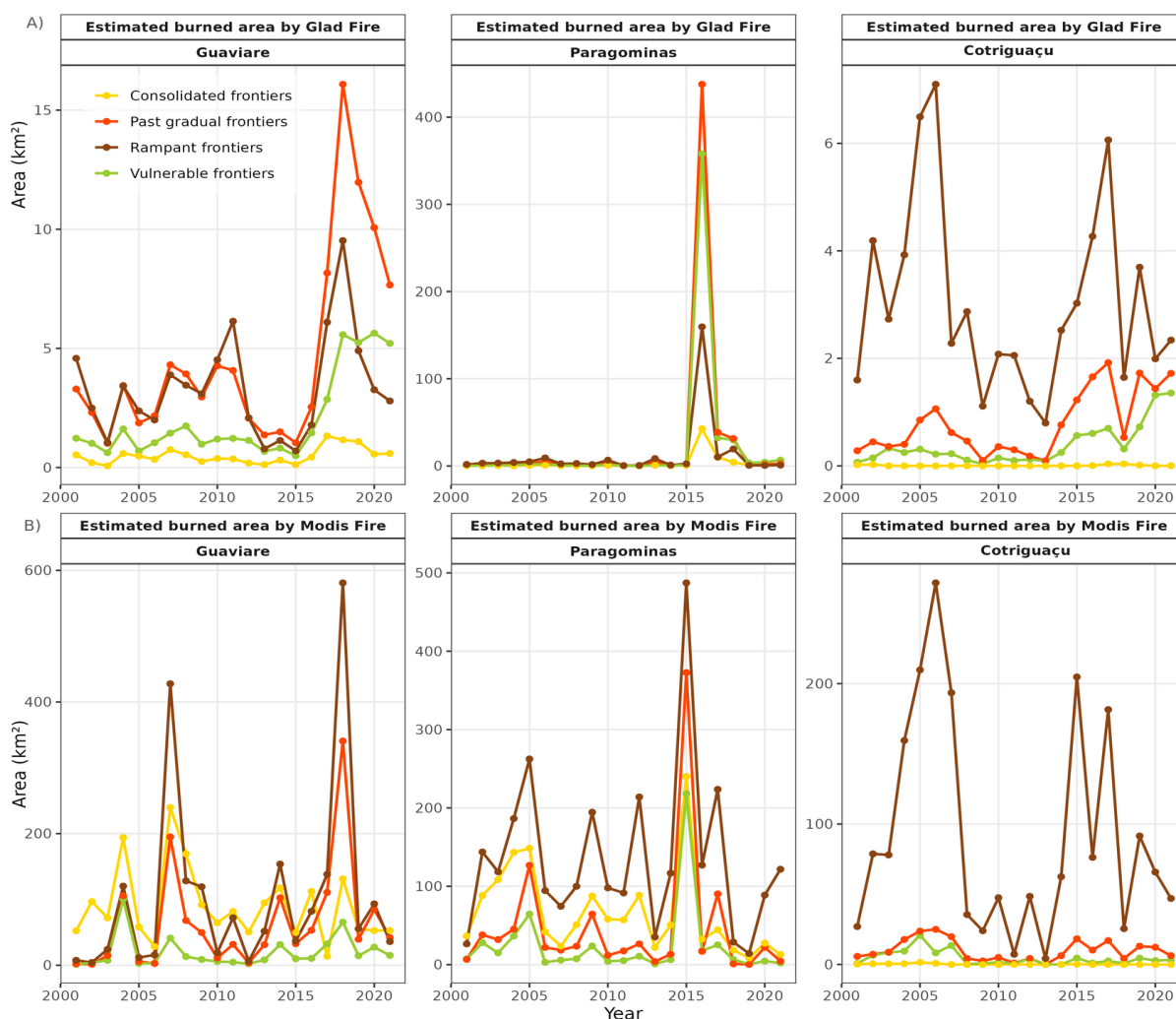


Figure 64: Annual burned area by archetype for the three study sites (Guaviare, Paragominas and Cotriguaçu) according to Glad Fire (A) and Modis Fire (B).

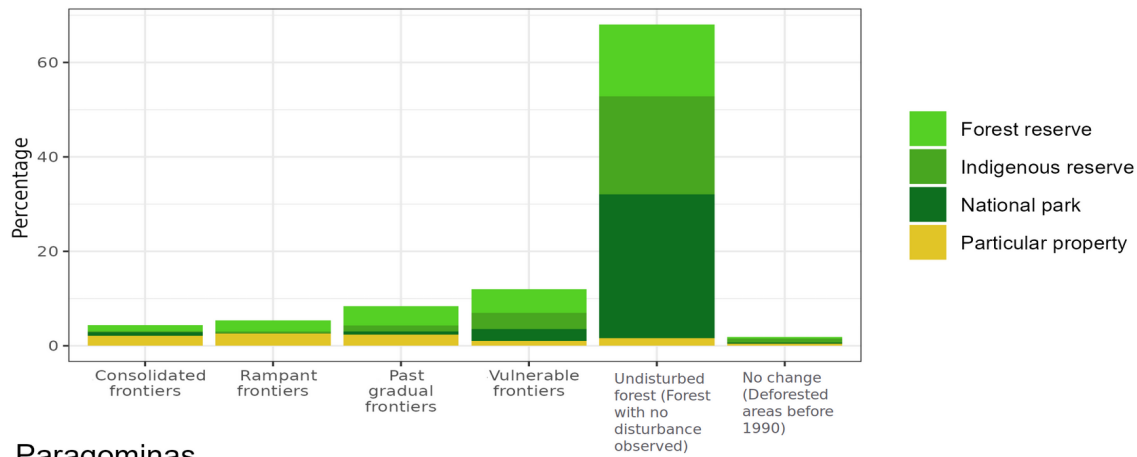
3.3.3 Distribution of archetypes in the legal framework in three subnational jurisdictions

In Guaviare, archetypes that have experienced deforestation—such as consolidated, rampant, and past gradual areas—reflect the status of forest reserves. In contrast, regions with low deforestation (vulnerable) or no changes at all (null) benefit from a strong legal and institutional framework, which includes protections like forest reserves, Indigenous reserves, and National Parks (Fig. 65). In Guaviare, two archetypes were predominantly found within the forest reserve: vulnerable frontiers (5%) and past gradual frontiers (4%). In particular properties, the archetypes were more evenly distributed, each occupying approximately 2% of the territory. Undisturbed forest was primarily

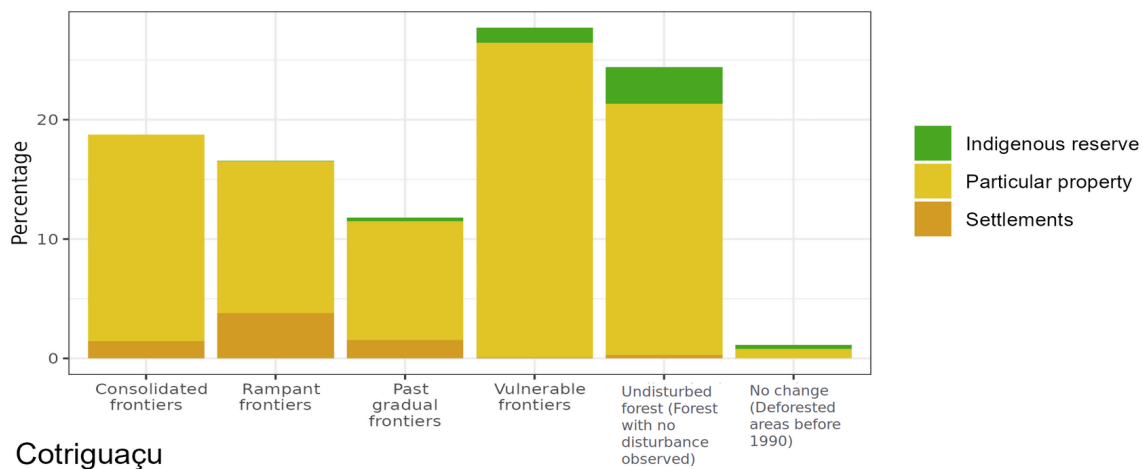
located within the national park (30%), but also had substantial presence within the indigenous reserve (21%) and the forest reserve (15%).

In the two Brazilian sites, the situation is very different. The majority of the area is occupied by particular properties. In Paragominas, all four archetypes are predominantly found on particular properties (Fig. 65). The undisturbed forest is mostly located on particular properties (21%) but also within an indigenous reserve. In this indigenous reserve, deforestation has begun (past gradual and vulnerable frontiers). In Cotriguaçu, undisturbed forests are found within the indigenous reserve (16%), in the national park (13%), as well as on particular properties (Fig. 65).

Guaviare



Paragominas



Cotriguaçu

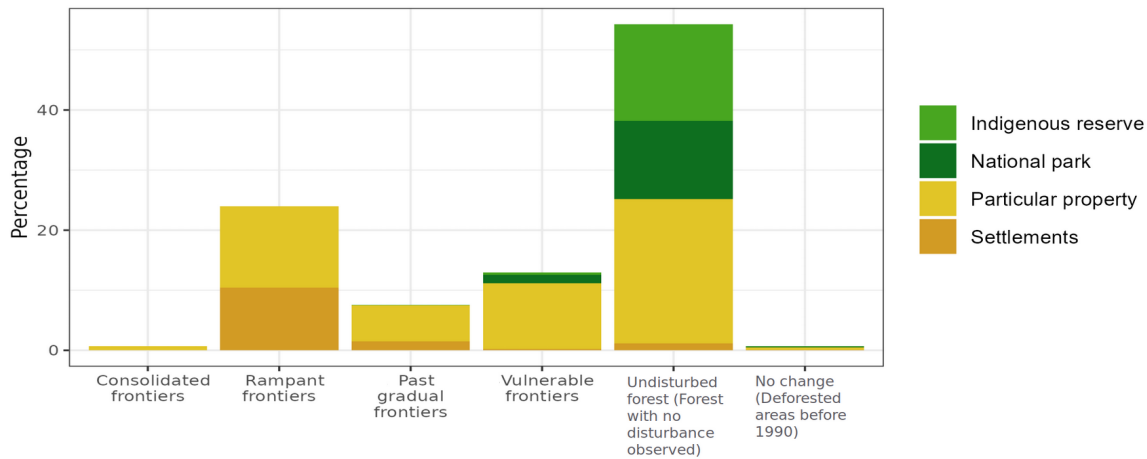


Figure 65: Distribution of archetypes, undisturbed forest and no change (deforested areas before 1990) across different land tenure categories at the three study sites: Guaviare, Paragominas and Cotriguaçu.

3.4 Discussion

3.4.1 Dynamics of deforestation and archetypes

Deforestation observed in Guaviare, Paragominas, and Cotriguaçu is primarily driven by pasture expansion, occurring through both, rapid processes characteristic of rampant frontiers and slower ones typical of past gradual frontiers. In the Brazilian territories, a decrease in deforestation rates has been evident since 2006, accompanied by relative stabilization of pasture areas. However, some forest-to-pasture conversions persist, as revealed in our land-use transition analysis for rampant frontiers in Paragominas between 2005 and 2021. This trend can be explained by three main factors: (1) the implementation of stricter environmental laws in the Amazon, with Paragominas serving as a pilot municipality in deforestation control (Piketty et al., 2015); (2) emerging economic opportunities linked to soybean cultivation, encouraging pasture-to-agriculture transitions (Osis et al., 2019); and (3) the intensification of agricultural production (Pacheco and Poccard-Chapuis, 2012), leading in some cases to pasture abandonment and subsequent forest regrowth (Chazdon and Guariguata, 2016). In rampant frontiers, forest degradation remains low and does not significantly influence land-use dynamics. In contrast, in Colombia's Guaviare, deforestation is more intense and continuous, primarily driven by direct forest conversion into pasture. There has also been a marked increase in deforestation after the 2016 peace agreement (Negret et al., 2019). In past gradual frontiers, deforestation proceeds more slowly, and degraded forest plays a greater role as an intermediate stage between undisturbed forest and pasture or mosaic of land uses.

The existence of two distinct archetypes rampant and past gradual frontiers reflects the heterogeneous institutional, socioeconomic, and ecological contexts shaping forest cover change. Rampant frontiers are typically located near main roads and secondary roads. These areas undergo more intensive deforestation due to reduced transportation costs, facilitated market access, and lower operational barriers. As the agricultural frontier extends into more remote regions, where conversion and maintenance costs rise, the deforestation process slows down, giving rise to past gradual frontiers. This

spatial logic applies to both Brazil and Colombia, where road infrastructure remains a key driver of land-use dynamics (Etter et al., 2006; Laurance et al., 2009; Soares-Filho et al., 2004).

Archetype distribution also suggests that institutional factors, such as land tenure regimes and colonization history, play a crucial role in forest cover change trajectories. Areas with long-standing settlement processes and consolidated land ownership tend to exhibit higher deforestation rates, as observed in Paragominas during the early 2000s (Osis et al., 2019), aligning with rampant archetypes. Conversely, in zones with tenure insecurity or unresolved land claims (Katz-Asprilla et al., 2024), land-use transitions occur more slowly, favoring past gradual archetypes, as observed in Guaviare. Population pressure further compounds this effect: rural settlements and population growth intensify forest conversion pressure (Caviglia-Harris and Harris, 2011; Line Carpentier et al., 2000; Pereira et al., 2022), especially in territories lacking effective regulation. Public policies such as Brazil's Rural Environmental Registry (CAR) (da Cruz et al., 2022) or anti-illicit crop programs in Colombia (Dávalos et al., 2021) may foster more moderate dynamics or even regrowth, as seen in Miraflores-Guaviare and parts of Paragominas.

In vulnerable frontiers, forest transformation is less intense, partly due to their remoteness and legal restrictions that prevent forest-to-pasture conversion. These areas are often located within or adjacent to legally protected territories such as national parks, indigenous reserves, or forest reserves, where land-use change is prohibited. Their inaccessibility also raises logistical and operational costs for extensive agriculture, deterring accelerated deforestation. This combination of geographic isolation and legal protection helps maintain the predominance of undisturbed forests.

In consolidated frontiers, particularly in Paragominas, forest dynamics resemble a classic forest transition: after a period of intense deforestation and drastic forest cover loss, a stabilization phase emerges, followed by slight increases in secondary vegetation. This dynamic suggests the landscape has reached a conversion threshold, after which processes of forest regrowth begin either due to land abandonment, conservation policies, or shifts in land use

(Carvalho et al., 2020). The Green Municipality initiative, which discourages further deforestation (Piketty et al., 2015), along with pasture-to-soybean conversion, has helped reduce pressure on undisturbed forests (Carvalho et al., 2020; Osis et al., 2019). In contrast, Guaviare does not yet exhibit signs of stabilization or reversal, likely due to weaker institutional capacity and limited territorial control.

3.4.2 Management priorities by archetypes

A critical aspect of territorial management is the need to limit the degradation of undisturbed forests within the vulnerable frontiers and past gradual frontiers archetypes. Although these areas still retain significant forest cover, they are increasingly exposed to pressures such as selective logging, understory fires, and edge effects from adjacent land uses (Lapola et al., 2023). Forest degradation is less detectable than deforestation, leading to significant gaps in estimation that undermine the capacity of forests to provide ecosystem services (Berenguer et al., 2021). In this context, the implementation of high-resolution monitoring systems, the strengthening of field-based enforcement, and the promotion of low-impact practices such as sustainable forest management are essential (Romero et al., 2015). Furthermore, legal recognition and community-based governance can serve as effective barriers to degradation processes (Arts et al., 2014).

Fire control is another central challenge, particularly in the rampant frontiers and past gradual frontiers archetypes, where its recurrence compromises both forest cover and agricultural productivity. In the rampant frontiers, dominated by agricultural and pasture lands, fires tend to be large-scale events resulting from uncontrolled burns for pasture management or agricultural expansion. These events have significant ecological impacts and are difficult to contain (Alencar et al., 2011; Aragão et al., 2018). In contrast, in the past gradual frontiers, less visible but frequent understory fires progressively degrade forests, affecting their structure and regrowth capacity (Alencar et al., 2006; Lapola et al., 2023). Addressing these two fire regimes requires differentiated strategies: in agricultural areas, strengthening farmer training, implementing early warning systems, and penalizing irresponsible fire use are essential; in

forested areas, the focus should be on prevention, remote sensing monitoring, and the restoration of affected zones.

Forest regeneration within consolidated and rampant frontiers represents a key opportunity for ecological restoration and the improvement of landscape connectivity. In consolidated frontiers, where pastures have reached a state of stability or even show signs of abandonment, an increase in natural forest regrowth has been observed. This trend has also been documented in other parts of the Amazon by previous studies (Chazdon, 2008; Nunes et al., 2020). Such regeneration processes should be actively managed through financial incentives, restoration programs, and technical assistance to ensure their permanence and prevent reconversion to productive land uses. In rampant frontiers, regeneration is more limited due to sustained agricultural expansion pressures; however, marginal lands and areas of low productivity could be allocated for assisted regeneration efforts (Brancalion et al., 2016). The implementation of agroforestry systems and the legal recognition of secondary forests as environmental assets can strengthen these processes. Moreover, incorporating regeneration strategies into territorial planning instruments, such as the Rural Environmental Registry (CAR) or designated exclusion zones for productive use, could enhance the long-term viability of forest recovery.

3.4.3 Legal and institutional framework

In Colombia, the protection of undisturbed forests is fundamentally based on the enforcement of legal conservation regimes such as National Natural Parks, Forest Reserves, and Indigenous Territories. These designations are defined by national laws such as Law 2 of 1959 and Decree 2811 of 1974, which establish conservation functions and restrict productive activities within these areas. Their effectiveness largely depends on the State's capacity to exert territorial control, as well as the strengthening of self-governance within indigenous territories (Rodríguez-de-Francisco et al., 2021). However, in regions such as the Department of Guaviare, where multiple legal protection instruments coexist, tensions persist due to illegal land occupation, livestock expansion, and illicit crop cultivation. This highlights the need to reinforce institutional presence and strengthen coordination with local communities to ensure the

effective conservation of strategic ecosystems (González-González et al., 2021; IDEAM, 2023).

In Brazil, although formal protection figures also exist, a key distinction lies in the co-responsibility assigned to private landowners through the Forest Code (Law 12.651/2012). This legal framework mandates the conservation of 80% of forest cover on rural properties located within the Legal Amazon, thereby positioning rural producers as key actors in forest conservation (BRASIL, 2012). However, the mere existence of legal instruments does not ensure compliance. As a result, the State has promoted complementary mechanisms of technical and financial support, such as the Rural Environmental Registry (CAR), the Environmental Regularization Programs (PRA), and multi-stakeholder agreements like the PCI (Produce, Conserve and Include) initiative, which combine economic incentives with environmental monitoring (Guariguata et al., 2017; Guerra, 2016). In municipalities like Cotriguaçu, these actions have contributed to deforestation reduction through more inclusive governance schemes and the integration of instruments such as REDD+. Thus, while Colombia emphasizes legal protection statutes, forest conservation in Brazil largely depends on the articulation of efforts between state institutions, private actors, and civil society to implement effective policies on the ground.

3.5 Conclusion

This chapter presents a comprehensive spatio-temporal assessment of forest cover change using an archetype based approach in three Amazonian study sites. We demonstrate that the four trajectory archetypes (consolidated, rampant, past gradual, and vulnerable frontiers) capture distinct land use trajectories, degrees of landscape fragmentation, and key drivers of change. Consolidated and rampant frontiers were dominated by extensive deforestation and pasture expansion, along with increasing degradation and the emergence of secondary forest regrowth and soybean cultivation, particularly in Paragominas. Past gradual frontiers exhibited slower deforestation, a more prominent role of degradation, and forest regrowth linked to pasture abandonment. Vulnerable frontiers remained largely forested, although early signs of degradation were detected.

Land-use transitions varied significantly across the three sites. In Brazil, conversions from pasture to soybean and regrowth forests were more common, whereas in Colombia, the dominant pattern was direct forest-to-pasture conversion. Fragmentation metrics confirmed increasing landscape fragmentation in rampant and past gradual frontiers, approaching levels observed in consolidated frontiers.

We highlight the urgent need for implementing fire management and control policies in rampant and past gradual frontiers, where fire plays a critical role in both agricultural practices and forest degradation. The spatial distribution of archetypes across legal land categories emphasizes the importance of protected areas in conserving undisturbed forests, especially in Guaviare. In contrast, the predominance of private landholdings in Brazil reinforces the relevance of governance tools such as the Rural Environmental Registry (CAR) and incentive-based sustainability programs. Our findings support the utility of trajectory archetypes as a robust framework to guide context-specific forest governance strategies and landscape-level land-use planning across the diverse Amazonian region.

CHAPTER 4- The CHALLENGES OF TERRITORIAL FOREST GOVERNANCE IN PRESSURED AREAS OF THE AMAZON

4.1 Context

Despite the implementation of various economic instruments, public policies, and restoration plans in the Brazilian Amazon, net deforestation rates remain alarmingly high (Silva Junior et al., 2020; Vancutsem et al., 2021). This persistent deforestation has pushed the Amazon rainforest to a critical tipping point, transitioning it from a carbon sink to a net source of carbon emissions (Aragão et al., 2018). This shift not only undermines its crucial role in climate change mitigation but also jeopardizes a wide range of ecosystem services and social benefits, negatively impacting biodiversity, the water cycle, and local communities (Bonan, 2008; Brien et al., 2015; Zhang et al., 2023).

Scientific evidence of these impacts is accumulating rapidly, outpacing the ability of state and municipal governments to reduce deforestation to established targets. These actors face the challenge of balancing environmental conservation with the need to promote economic growth in their territories. In 2024, on the Amazon's frontier, the expansion of the livestock and agroindustry sectors, along with illegal logging, remain the primary drivers of deforestation and forest degradation (Kruid et al., 2021).

In this context, territorial forest governance must adopt a multidimensional approach, integrating political, economic, legislative, and social levers to effectively regulate deforestation (Arts et al., 2014; McDermott et al., 2015; Ostrom, 2012). However, the implementation of these strategies is hindered by the influence of powerful economic actors, particularly those involved in land grabbing, and by the constant pressure to drive economic development. Despite these challenges, some states and municipalities have made significant progress in implementing forest conservation policies, demonstrating that it is possible to reconcile development with environmental protection (Griffin et al., 2002; Guerra et al., 2014; Piketty et al., 2015).

However, these measures remain fragile and reversible, contingent on the national political context and the demands of the international market for Amazonian commodities (Deininger, 2011; Escobar, 2019). The challenges of

forest governance in the Brazilian context extend far beyond forest management alone, as they are deeply intertwined with the intersectoral and political complexity of the territory (Fischer et al., 2020). As highlighted by Agrawal et al. (2008) and PROFOR (2011), territorial forest governance must address all direct and indirect drivers of deforestation and degradation, as well as their interactions. Specifically, it must:

i) Enforce legislative frameworks to combat illegal logging and land encroachment, as well as mandate the restoration of protected areas within agricultural lands. ii) Ensure compliance with zero-deforestation commitments from the private sector. iii) Uphold the rights of Indigenous peoples and traditional communities over their territories. iv) Facilitate negotiations among stakeholders with divergent interests, such as large-scale farmers and industries versus Indigenous communities, and among various local or regional institutions. v) Harmonize contradictory public policies, such as REDD+ initiatives, with those promoting agricultural expansion. vi) Develop incentives for agricultural intensification and provide technical support while decarbonizing sectors and regulating supply chains across different markets. vii) Align conservation projects led by international cooperation with local development priorities. viii) Promote sustainable forest management in accordance with FSC (Forest Stewardship Council) criteria.

Faced with these multiple tensions, territorial forest governance must leverage innovative and integrative solutions. This includes strengthening the capacity of diverse stakeholders to collaborate, overcome power asymmetries, and develop transformative approaches that reconcile conservation, sectoral development, human rights, and agroecological transitions. Such efforts are essential to address the complex and interconnected challenges of deforestation, land use, and sustainable development in the Amazon.

4.1.2 Definition of forest governance

According to Fischer (2020), forest governance refers to the set of processes, institutions, and mechanisms through which decisions regarding forest management, use, and conservation are made and implemented. The addition of the term "territorialized" highlights the importance of adapting forest

governance to local socio-environmental contexts, enabling decision-making and policy implementation that are responsive to specific territorial dynamics.

This definition encompasses the interactions among a broad range of stakeholders including government bodies, local communities, NGOs, and the private sector and the legal, political, and social structures that shape forest management. Fischer emphasizes that effective and sustainable governance depends on stakeholder participation, transparency, accountability, and law enforcement.

Complementing Fischer's work, other institutions such as the European Forest Institute (EFI) stress that territorialized forest governance must adopt a holistic and integrated approach, incorporating environmental, social, economic, institutional, and cultural dimensions. This model should also rely on multi-level and multi-actor coordination, while aligning public policies with the specific needs of local territories.

Based on these frameworks, five core principles underpin territorialized forest governance:

1. Multi-level and Multi-actor Approach Territorial forest governance requires coordination across jurisdictional levels (local, regional, national, and international), as well as among diverse actors. As Ostrom (2009) argues, addressing deforestation demands cross-scale collaboration to prevent policy contradictions. Locally, stakeholders include forest-dependent communities; regionally and nationally, actors enforce policies and provide support; internationally, mechanisms like REDD+ address global challenges such as climate change and illegal logging.

2. Multi-level and Multi-actor Approach Territorial forest governance requires coordination across jurisdictional levels (local, regional, national, and international), as well as among diverse actors. As Ostrom (2009) argues, addressing deforestation demands cross-scale collaboration to prevent policy contradictions. Locally, stakeholders include forest-dependent communities; regionally and nationally, actors enforce policies and provide support;

internationally, mechanisms like REDD+ address global challenges such as climate change and illegal logging.

3. **Accountability and Institutional Transparency** Effective governance requires mechanisms that promote transparency and accountability in decision-making. Local stakeholders should be empowered to participate in planning processes, while institutions must be held accountable for their actions. Research has shown that institutional transparency reduces corruption and improves environmental outcomes (Fischer et al., 2016).

4. **Recognition of Local and Indigenous Rights** A territorial approach acknowledges the land and cultural rights of local and Indigenous communities. These groups often possess traditional ecological knowledge and a long-standing relationship with forest ecosystems. Studies show that when these communities are involved in governance, deforestation rates are lower and forest management is more sustainable (Chhatre & Agrawal, 2009).

5. **Intersectoral Policy Integration and Coordination** Forest governance must align with policies in related sectors such as agriculture, economic development, and conservation. Integrated approaches help to prevent conflicts, promote synergies, and enhance territorial sustainability. Policy coherence is essential for reducing trade-offs and increasing local acceptance of governance frameworks (Fischer et al., 2019).

According to (EFI, 2024; Kissinger et al., 2012), the effectiveness of forest governance relies on five main factors:

1. **Availability of Information on Forest Ecosystems and Landscape Dynamics** This refers to the accessibility of accurate and comprehensive data on the state and functioning of forest ecosystems, as well as the various landscape components that influence forest dynamics. Such information is crucial for supporting decision-making and evaluating the impacts of interventions both before (ex-ante) and after (ex-post) implementation (Jagger et al., 2010).

2. **Alignment of Policies and Decisions Among Institutions** Effective governance requires the alignment of public and private instruments around shared conservation and forest management objectives. This ensures that the actions

of various institutions, whether directly or indirectly involved in forest management, are complementary and coherent (Lambin et al., 2014).

3. Institutional Capacities This factor highlights the need for adequate material, human, and financial resources to enable institutions and stakeholders to participate effectively in forest policy-making and management activities (Toni, 2011).

4. Reduction of Power Asymmetries Among Actors and Institutions Addressing power imbalances between different actors and institutions is essential for fostering equitable and inclusive governance. This involves creating mechanisms to ensure that all stakeholders, particularly marginalized groups, have a voice in decision-making processes (Biermann, 2010; Brockhaus et al., 2014).

5. Shared Vision and Common Objectives for Forest Management A unified vision and shared goals among diverse stakeholder groups are critical for effective forest governance. This alignment ensures that all actors work collaboratively toward sustainable forest management and conservation objectives (Ros-Tonen et al., 2008; Scholz, 2005).

The municipality of Cotriguaçu in Brazil presents a complex case of frontier forest governance shaped by overlapping colonization dynamics, agricultural expansion, institutional enforcement, and territorial planning efforts. While deforestation has been significantly reduced due to coordinated interventions such as PPCDAm inclusion, CAR implementation, REDD+ pilots, and the role of MP-MT the municipality continues to face chronic governance challenges. These challenges include the legacy of land tenure irregularities, structural dependence on extensive cattle ranching, weak municipal capacity, high reliance on external financial transfers, and persistent asymmetries in actor power and access to support mechanisms.

Despite these constraints, Cotriguaçu has made notable advances in multilevel forest governance through participatory mechanisms (CMMA), environmental funds (FUMDEMA), and integrated initiatives (PCI, REDD+, PRONAF). The coordination of conservation efforts with socio-economic development,

particularly via family farming and low-carbon supply chains, illustrates a growing potential for territorial approaches to forest governance.

Cotriguaçu thus represents a good case study to deepen the issue of territorial governance. The theme of this work is to evaluate the opportunities and obstacles for more effective territorial forest management. One of the outcomes of this doctoral research is to provide more precise and detailed information on the evolution of forest cover, with the aim of supporting more effective decision-making. It therefore meets the first condition for effective territorial governance.

The appropriation of this information and its integration into decision-making implies that stakeholders share a common and unified vision of forest-related issues. The research question of this work is therefore: do the local actors share a common vision of the system (forest management), or are they focused on only certain components of it?

Our hypothesis is that all actor types or institutions share a similar and comprehensive understanding of territorial dynamics. However, there are trends that run counter to this vision. An institution's specific mandate tends to concentrate its attention on a particular segment of the territorial system in which it operates. This does not preclude a broader understanding of the system as a whole, but in practice, daily management tends to be fragmented, with decisions made without fully considering their direct or indirect impacts on forest dynamics. We hypothesize that the “observations” made by each institutional category reflect their operational roles, and thus their position in relation to the Geist & Lambin framework. For instance, actors closely involved with forest dynamics such as logging enterprises are expected to mention more frequent observations linked to direct impacts.

Brazil's environmental governance history has long been marked by deep-seated tensions between contrasting perceptions of natural spaces. These tensions are rooted in the state-led territorial colonization policies launched in the 1960s and persist in contemporary debates. As elsewhere, we observe a polarization between a utilitarian view of nature, emphasizing its economic

exploitation, and a biocentric view, recognizing the intrinsic value and rights of ecosystems. Kröger (2017) provides a detailed analysis of this divide, classifying actor positions along a gradient of environmental ideologies and examining the implications of these positions for decision-making and governance outcomes.

In this context, the territorial forest governance framework must not only account for institutional responsibilities and structural constraints but also address the divergent worldviews that shape actor engagement and influence governance practices.

4.1.2.1 Theoretical framework

Forest governance comprises the constellation of norms, policies, institutions, and processes that regulate the management and conservation of forest resources. Contemporary scholarship identifies four principal theoretical approaches that underpin forest governance: the Theory of the Commons, Multilevel Governance, the Socio-Ecological Systems Approach, and the Governance-Deforestation Nexus.

Core Theoretical Approaches

Theory of the Commons

The Theory of the Commons emphasizes the capacity of communities to govern shared natural resources through self-organized systems of rules and social norms. Ostrom (1990) demonstrated that collective action, local knowledge, and institutional arrangements at the community level can facilitate sustainable management of common-pool resources such as forests. This perspective challenges the assumption that only state control or market mechanisms can prevent the over-exploitation of shared resources.

Multilevel Governance

Multilevel governance highlights the importance of coordination and cooperation across different scales of governance local, regional, national, and international (Cash et al., 2006). This framework argues that effective forest governance requires vertical and horizontal linkages among institutions,

promoting coherence and synergy across jurisdictions and actor groups. It is particularly relevant in contexts where environmental challenges transcend political and administrative boundaries.

Socio-Ecological Systems Approach

This approach integrates ecological and social dimensions, recognizing their mutual interdependence in the context of forest management (Berkes et al., 2008). It advocates for adaptive and participatory management strategies that strengthen ecosystem resilience and safeguard the livelihoods of communities dependent on forest resources. The socio-ecological perspective underscores the dynamic and co-evolving nature of human-environment systems.

Governance and Deforestation

This strand of research evaluates the effectiveness of governance mechanisms in mitigating deforestation and forest degradation. Evidence suggests that decentralized and inclusive governance structures can significantly reduce forest loss by empowering local actors and promoting sustainable land-use practices (Fischer et al., 2020). This approach links governance quality directly to environmental outcomes, emphasizing accountability, participation, and institutional robustness.

Conditions for Effective Forest Governance

Effective forest governance is characterized by institutional arrangements that support decision-making, monitor environmental and social impacts, and adapt to changing conditions. The literature identifies several key indicators that enable the assessment and improvement of governance systems (Fischer et al., 2020). These indicators can be grouped as follows:

Key Governance Indicators

1. Transparency and Accountability

The presence of mechanisms that ensure openness in decision-making and hold forest managers accountable to stakeholders is vital. These mechanisms foster trust, deter corruption, and enhance policy effectiveness.

2. Stakeholder Participation

Inclusive decision-making processes involving government agencies, civil society organizations, local communities, and the private sector ensure that governance outcomes reflect a plurality of interests and knowledge systems. Participation strengthens legitimacy and compliance.

3. Enforcement of Laws and Regulations

The effectiveness with which forest-related legislation is implemented and enforced is a core determinant of governance performance. Strong enforcement frameworks reduce illegal logging and associated environmental harms.

4. Institutional Capacity

The availability of financial, human, and technical resources within local institutions significantly affects their ability to implement forest governance strategies. Capacity-building efforts are therefore central to governance reform.

5. Conflict Resolution Mechanisms

The presence of fair and accessible mechanisms to resolve disputes over forest use contributes to social cohesion and sustainable resource management. Such mechanisms reduce conflict and support long-term cooperation among stakeholders.

Agency and Structure in Forest Governance

Fischer et al. (2020) emphasize that effective forest governance arises from a dynamic interaction between agency and structure. Structural elements such as legal frameworks, institutions, and market forces provide the contextual "rules of the game" that shape actors' behavior. Conversely, agency refers to the capacity of individuals and groups to act independently, make decisions, and influence governance processes based on their motivations, perceptions, and resources (Archer, 2003).

In this context, agency includes the roles played by local communities, non-governmental organizations (NGOs), and sub-national governments in initiating and implementing forest conservation actions. Structure, on the other hand, encompasses national and international laws and institutions, such as the Brazilian Forest Code (Law No. 4.771, in force from 1965 to 2012) and its successor, the Brazilian Forest Law (Law No. 12.651), which govern land use, deforestation, and environmental compliance.

Importantly, several governance indicators relate either primarily to agency (e.g., stakeholder participation), to structure (e.g., legal frameworks), or to the intersection of both (e.g., institutional capacity). Thus, a comprehensive governance strategy must foster both strong institutional structures and the empowerment of local actors.

Fischer (2020) links various governance indicators to either **agency**, **structure**, or **both** (see Table 10, to be revised: grey = structure; black = agency; white = both or unclassified).

Table 10: Six thematic areas with their respective indicators for measuring governance, including indicators related to agency, indicators related to structure, and indicators related to both agency and structure; adapted from Fischer et al. (2020).

1 Forests tenure	2 Land use	3 Forest management
-Forest ownership and use rights	-Land use planning	-Forest legal and policy framework
-Tenure dispute resolution	-Land use plan implementation	-Forest strategies and plans
-State forest ownership	-Sectoral land use	-Forest law enforcement
-Concession allocation	-Forest classification	-Forest management practices
		-Forest monitoring
4 Forest revenues	5 Institutions	6 Cross cutting issues
-Forest charge administration	-Legislature	-Public participation in decision-making

-Forest revenue distribution	-Judiciary	-Public access to information
-Benefit sharing	-Executive agencies	-Financial transparency and accountability
-Budgeting	-Private sector	-Anticorruption measures
	-Civil society	

This analytical distinction is particularly relevant for understanding forest governance in Amazonian territories, especially in Brazil, where legal obligations—such as the requirement to restore Permanent Protection Areas (APPs) or partially reforest deforested land within rural properties—are established by federal law. For example, under Brazil’s Forest Code, landowners in the Amazon are required to conserve 80% of their property as Legal Reserve, leaving only 20% for productive use. However, it is ultimately up to individual landholders to comply with these requirements, depending on their personal motivations, resources, and capacity for implementation (Arts et al., 2014).

In this study, the governance indicators will be used in articulation with the theoretical framework of structure and agency. Some reflect institutional dimensions (legal frameworks, public policies), while others account for actors’ capacities for action and adaptation. This analytical link structures the interpretation of empirical materials (interviews and workshops), by showing how actors deal with constraints or redefine the territorial rules.

4.1.3 Contextual Overview: The Case of Cotriguacu

4.1.3.1 *Territorial characteristics*

The municipality of Cotriguacu, located in the northern region of Mato Grosso, Brazil, spans a total area of 9,149 km². Its territory is divided into multiple land-use categories: conservation units such as the Juruena National and State Parks (14%), Indigenous Lands (Escondido IL, 18%), settlement projects (14%), and rural and urban properties (54%) (IBGE, 2023). Notably, approximately 74% of

the municipal area remains covered by native forest, indicating its high potential for biodiversity conservation and sustainable land management.

Historically, Cotriguaçu was inhabited by the Rikbaktsa people, whose rights were formally recognized with the demarcation of the Escondido Indigenous Lands in 1998 (Povo Rikbaktasa, 2014). The Rikbaktsa's economy is largely based on the collection of non-timber forest products, subsistence agriculture, and, more recently, the commercialization of artisanal crafts.

Cotriguaçu was planned by Cotriguaçu Colonizadora do Aripuanã S/A, a cooperative based in Paraná, as a colonization project aimed at relocating family farmers from southern Brazil. Family farming has since become a dominant socio-economic feature in the municipality. In 2012, approximately 1,500 families were engaged in family farming, a number that rose to 1,955 by 2023, with 2,229 settlement plots established under the federal INCRA program (Município de Cotriguaçu, 2023).

4.1.3.2 Governance Initiatives and Sustainable Development

Several projects supported by the Amazon Fund have significantly strengthened social organization in Cotriguaçu. Implemented by the Instituto Centro de Vida (ICV), these initiatives empowered local associations, such as the Associação de Coletores de Castanha do Projeto de Assentamento Juruena (ACCPAJ) and the Associação Indígena Aldeia Babaçuzal (AIABA). Additionally, the Instituto Ouro Verde (IOV) established Banco Raiz, a financial mechanism that supports agroecological transitions among family farmers (Mamede et al., 2024).

At the state level, the REDD+ mechanism, introduced in 2013, provided a foundational framework for the “Produce, Conserve, Include” (PCI) strategy, launched at COP-21 in 2015. The PCI strategy promotes intersectoral collaboration among government, civil society, and the private sector to eliminate deforestation from value chains by 2030. In Cotriguaçu, PCI has enabled funding for increased productivity in sustainable agriculture and

forestry, conservation of native vegetation, restoration of environmental liabilities, and the socio-economic inclusion of smallholders.

PCI Strategy Objectives in Cotriguaçu

- **Produce:** Encourage sustainable agricultural and livestock practices that increase productivity while maintaining existing land use boundaries.
- **Conserve:** Safeguard native vegetation through conservation and ecological restoration to ensure ecosystem service provision.
- **Include:** Promote the socio-economic integration of local communities in sustainable development initiatives.

4.1.3.3 Adapting the Geist and Lambin Framework

Changes in forest cover are generally evaluated through deforestation metrics. However, forest dynamics in tropical regions also include degradation and regeneration processes. Geist and Lambin (2002) provided a foundational framework identifying both direct drivers such as agricultural expansion, timber extraction, and infrastructure development and indirect drivers, including demographic shifts, economic pressures, and political-institutional conditions.

Despite its comprehensive scope, the original Geist and Lambin model does not explicitly incorporate the role of institutions, which are pivotal in mediating forest governance outcomes in Amazonian territories. This study builds upon the original model by including forest degradation and regeneration, while also integrating institutional factors to better capture the specific dynamics at play in Cotriguaçu (Fig. 66).

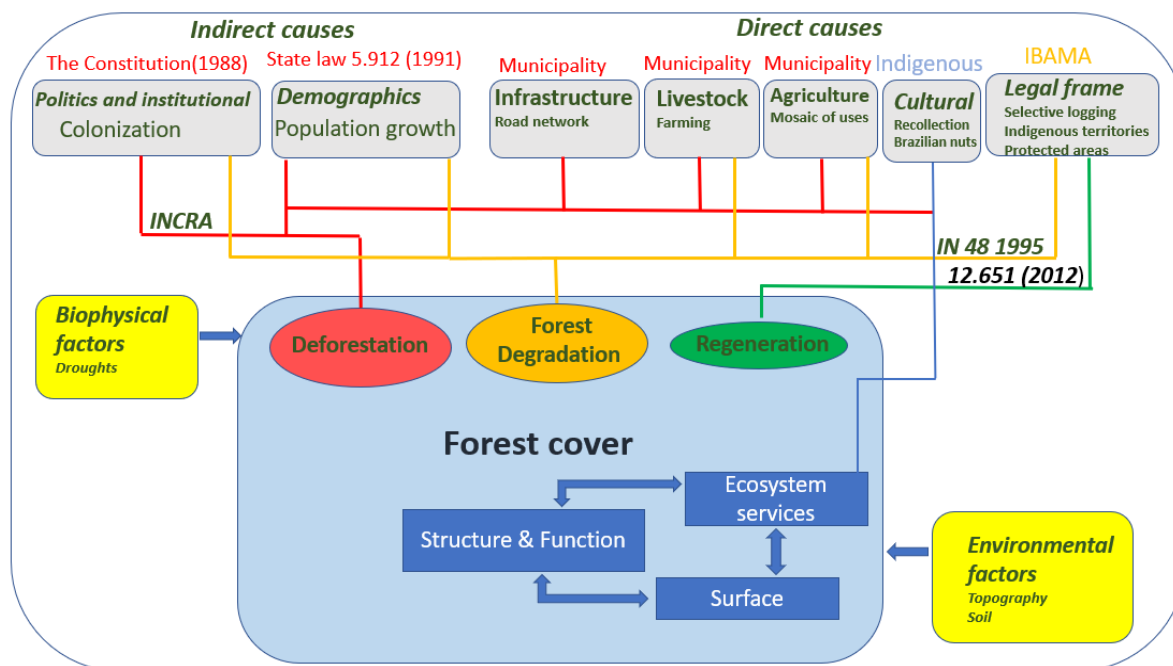


Figure 66. Relationships between the causes of direct and indirect disturbances, the processes (deforestation, degradation, and regeneration), and their consequences for forest cover change. Adapted from Geist & Lambin (2001).

Indirect Drivers of Forest Change

Policy and Institutional Factors

Cotriguaçu's colonization began in 1978 under Colonizadora Juruena Empreendimentos, a private company promoting land settlement. Early land purchases occurred around 1984, allowing for the implementation of numerous settlement projects that attracted families from other states, notably Mato Grosso do Sul and Rondônia. New communities such as Nova Esperança, Nova União, and Ouro Verde emerged during this period. Others settled in urban areas, often taking employment in the timber sector.

Demographic Factors

The demographic landscape changed rapidly with the formal establishment of Cotriguaçu as a municipality in 1991. The population grew from 4 379 inhabitants in 1996 to 14 900 in 2010 and reached 20 717 by 2021, raising population density from 0.48 to 2.27 persons/km² in 25 years. Despite this growth, the municipality continues to report a low Human Development Index

(HDI) of 0.60 (IBGE, 2023), signaling ongoing challenges in education, nutrition, and income security.

Direct Drivers of Forest Cover Change

Road Infrastructure and Colonization

Infrastructure development particularly road construction has directly facilitated land conversion. The opening of highways MT-208 and MT-170 served as key access routes for settlement and agriculture. Road density increased from 0.0073 km/km² in 1998 to 0.16 km/km² by 2006, largely supporting pasture development, which now occupies 23% of Cotriguaçu's area (Município de Cotriguaçu, 2023).

Figure 67 illustrates the correlation between infrastructure expansion and deforestation peaks between 1998 and 2005, followed by stabilization.

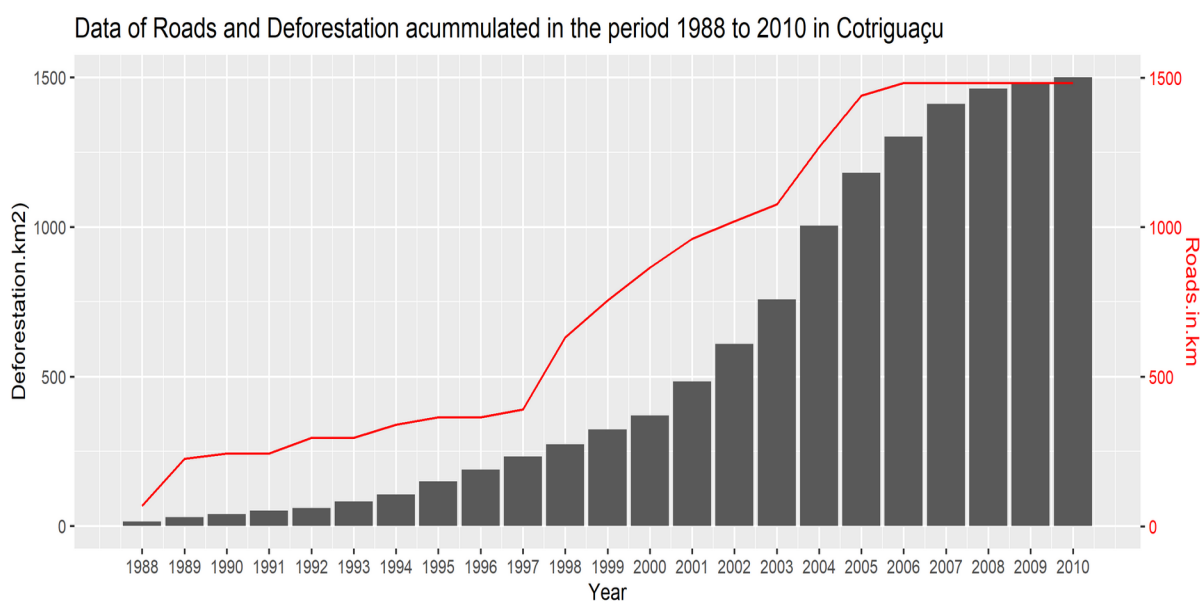


Figure 67: Cumulative road expansion and deforestation in Cotriguaçu. Source : Município de Cotriguaçu 2023.

Agricultural and Livestock Expansion

Cattle ranching is a major driver of land use change. By 2008, 19% of the forest cover in Cotriguaçu had been cleared for agricultural purposes. Livestock numbers grew from 50,000 in 2002 to 220,000 in 2008 (Fig. 68) . Across four

rural communities, livestock accounts for 34% of household income, followed by salaried labor, crops, and miscellaneous income sources (each at 16%).

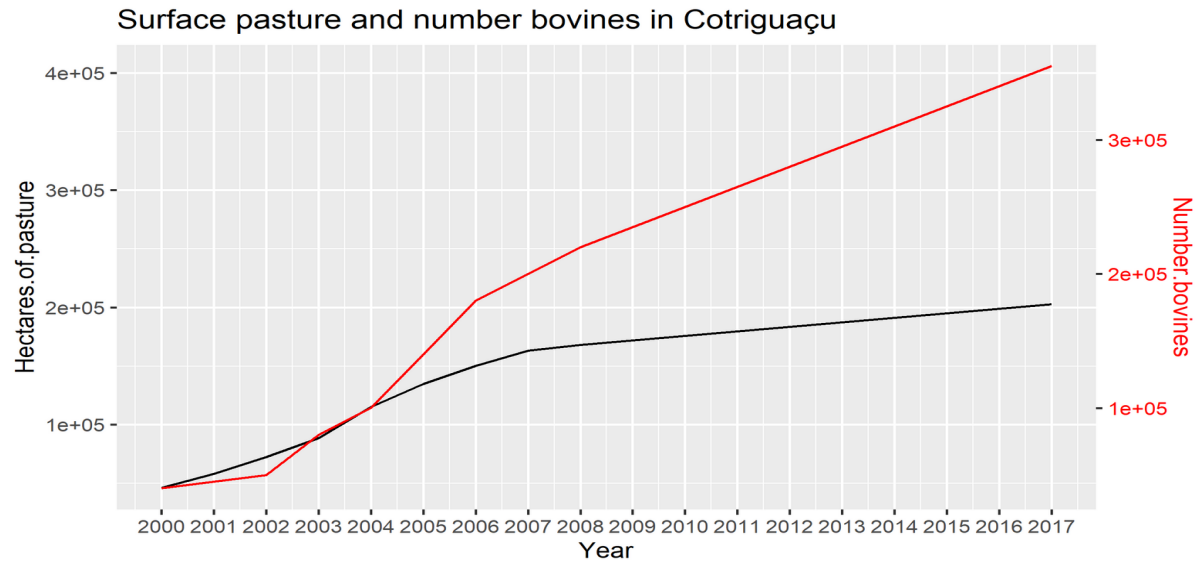


Figure 68: Temporal trends of pasture expansion and number of bovines in Cotriguaçu from 2000 to 2017. Source: IBGE 2023.

Timber Industry

Mato Grosso is Brazil's second-largest timber-producing state, accounting for 31% of national output. In 2009, Cotriguaçu housed 15 timber companies that consumed approximately 129 million m³ of logs annually, with the period between 2000 and 2008 marking the peak of forest degradation. Figure 69 reflects this degradation trend.



Figure 69. Details household income distribution by source (Sills et al., 2014).

Selective Logging and Forest Management

The forest sector in Cotriguaçu generates between 2,172 and 2,292 jobs, primarily through licensed Sustainable Forest Management Plans (PMFS) on private lands. However, only 33% of timber entrepreneurs own land; the rest rely on shared or rented properties. With 382,000 hectares of privately held forest suitable for sustainable logging, Cotriguaçu has the potential to increase its logging capacity by 17%.

Brazil Nut Harvesting

Indigenous territories, particularly the Escondido IL, occupy 1 650 km² (18% of municipal territory) and contain 99% of Cotriguaçu's remaining natural forest. Brazil nut collection is a key economic activity in these lands and adjacent PMFS-designated areas. In 2008, a processing unit with a storage capacity of 50 tons was established, receiving 32 tons of Brazil nuts from Rikbaktsa territory.

Legal Instruments and Institutional Measures

A robust legal framework is essential for maintaining production forests and safeguarding areas critical for ecosystem services, such as water resources. In Brazil, key legislation and institutional initiatives have significantly shaped forest management and landscape dynamics in municipalities like Cotriguaçu.

In 1995, the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) issued Normative Instruction No. 48, which established regulations for selective logging in primary forests within the Legal Amazon (BRASIL, 1995). This regulation influenced patterns of forest degradation, with the Instituto Centro de Vida (ICV) mapping approximately 9 122 hectares of selectively logged areas in Cotriguaçu by 2019.

Further advancements came with the enactment of Law No. 12,651/2012, commonly referred to as the New Forest Code. This legislation redefined environmental compliance on rural properties by:

- Establishing Permanent Preservation Areas (APPs);

- Mandating Legal Reserves;
- Linking environmental obligations to the Rural Environmental Registry (CAR).

The New Forest Code facilitated landscape restoration efforts, notably through the "Semeando Novos Rumos em Cotriguaçu" project, funded by the Amazon Fund. This initiative invested R\$ 1.57 million, enabling the restoration of 134 hectares of APPs.

At the federal level, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), combined with the DETER real-time deforestation monitoring system, contributed to a marked reduction in deforestation between 2005 and 2010, following peak rates observed from 2000 to 2005 (~300 km² in Cotriguaçu) (Piketty et al., 2015).

Environmental and Biophysical Drivers

Topography and Soil Conditions

Cotriguaçu lies within the Apiacás-Sucunduri Plateau and the Southern Amazonian Interplateau Depression, areas characterized by gentle slopes and relatively accessible terrain. These features make the region particularly suitable for pasture establishment and mechanized agriculture, thereby increasing its susceptibility to deforestation and forest degradation.

Climate Variability and Drought

The Amazon region has experienced recurring extreme droughts linked to El Niño-Southern Oscillation (ENSO) events (e.g., 1982, 1987, and 2015). The 2015 drought, in particular, likely contributed to increased fire incidence in Cotriguaçu, consistent with regional patterns (Aragão et al., 2018; Berenguer et al., 2021).

Forest Cover Dynamics: Deforestation, Degradation, and Regeneration

Forest cover change in Cotriguaçu is characterized by three key processes: deforestation, forest degradation, and natural regeneration, each following distinct temporal trends:

- Deforestation totaled 2 404.22 km² between 1990 and 2021, with:
 - o A rapid expansion phase from 1990 to 2004, rising from 10.23 km² to 312.74 km² annually.
 - o A slower phase from 2005 to 2021, averaging 74.92 km²/year.
- Forest degradation followed a similar trajectory:
 - o From 9.56 km² in 1990 to 51.23 km² in 2004.
 - o Stabilizing from 2005 to 2021 at an average of 27.07 km²/year.
- Regeneration reached a total of 103.87 km² (1990–2019):
 - o Modest annual gains below 4 km² until 2009.
 - o Significant increases post-2010, with peaks in 2012 (23.14 km²) and 2019 (18 84 km²).

Impacts on Ecosystem Services

The consequences of forest cover change extend beyond carbon emissions to broader disruptions of ecosystem functionality:

Carbon Emissions: Deforestation and degradation release significant amounts of CO₂, undermining tropical forests' role as carbon sinks (Baccini et al., 2012; Sasaki et al., 2016).

Microclimate Alteration: Selective logging opens forest canopies, affecting energy and water cycles and increasing solar radiation (albedo), temperature, and humidity deficits (Huang et al., 2020; Laurance et al., 2011).

Fragmentation: Deforestation contributes to the proliferation of forest fragments approximately 5,000 new fragments per year in the Brazilian Amazon between 1999 and 2002 (Broadbent et al., 2008). The Fragmentation damage:

Connectivity between habitats, reducing ecological resilience.

Movement and survival of species, particularly large mammals, by isolating populations in degraded patches (de Almeida et al., 2020; Montibeller et al., 2020).

4.1.4 Chapter structure plan

In the first part, we introduce the conceptual and methodological framework guiding our analysis of forest governance and land-use dynamics in Cotriguaçu. This section presents the key research questions, the theoretical foundations related to multi-actor governance and the role of restoration instruments in Cotriguaçu. It also details the participatory methods used during the workshops, including actor mapping and discourse analysis, and outlines the criteria for stakeholder selection.

In the second part, we present the analyzes whether stakeholders in Cotriguaçu share a unified understanding of the forest territorial system, focusing on point 5 of EFI's governance indicators. Moreover of the analysis the convergence and divergence in perceptions among institutions representatives regarding environmental challenges and forest restoration. Particular attention is given to the technical, financial, and institutional factors identified as enabling or constraining the restoration of Permanent Preservation Areas (APPs).

In the third part, we develop a critical discussion based on three key themes: (1) the partial convergence of stakeholder perspectives and its implications for territorial governance; (2) the tension between institutional structure and the adaptive agency of producers and industries; and (3) the opportunities and limitations of current restoration instruments. Each theme is discussed in light of the broader literature on environmental governance and policy implementation.

In the final part, we draw general conclusions regarding the conditions for effective and inclusive governance of forest restoration in Cotriguaçu. We emphasize the need for policy approaches that bridge normative frameworks and local realities, and for strengthening multi-level coordination and

participatory mechanisms to foster legitimacy, equity, and ecological outcomes.

4.2 Methodology to elicit and analyse the actor's vision of forest governance

In this section, we describe the methodology used to test the two hypotheses concerning the existence of a shared vision of forest governance among institutions and key stakeholders. The analysis was conducted in several phases using a combination of qualitative tools. First, by semi-structured interviews, we elicited the perceptions of forest governance held by stakeholders and their respective institutions, as well as the types of information they considered necessary to improve forest management. In the second phase, we organized participatory workshops in which two distinct stakeholder groups co-constructed models for the restoration of Permanent Preservation Areas (APPs). These models were subsequently compared to assess potential convergence or divergence in governance perspectives.

4.2.1 Semi-structured Interviews

To develop relevant and useful indicators for local stakeholders, these indicators must possess key characteristics: they should be easily interpretable and enhance the capacity of stakeholders and institutions responsible for forest management to translate provided information into concrete actions. According to Kenney et al. (2016), the development of indicators requires two essential analyses: (1) understanding stakeholders' perceptions of forest dynamics, and (2) assessing their need for actionable information.

To address these aspects, semi-structured interviews were conducted with 14 stakeholders in the municipality of Cotriguaçu, whose institutional affiliations were selected to reflect the different interactions between causes and processes of forest dynamics as comprehensively as possible. The questions posed (Annex 1) focused on the challenges stakeholders face in their professional activities, the solutions they envision, and the type of information they require to improve their decision-making processes.

Given that each institution operates within the scope of a specific mandate, it is expected that actors will focus more closely on certain aspects of the territorial system that align with their operational responsibilities. While this does not preclude a broader understanding of territorial dynamics, day-to-day management often leads to decisions being made without a full consideration of the system's overall functioning or of the direct and indirect impacts of those decisions.

We therefore hypothesize that the types of “observations” made by actors are shaped by their institutional function and position within the territorial governance system. Accordingly, actors whose roles place them in close proximity to forest dynamics such as logging companies are more likely to report observations related to processes or proximate causes, rather than to underlying drivers or structural factors.

4.2.2 Stakeholder categories

The limitations related to both the availability of stakeholders and the time allocated for fieldwork within the framework of this thesis resulted in a total of 14 interviews (Table 11). Stakeholders were classified into three categories, based on their affiliation and role in forest governance and land use: industries, farmers and institutions.

Table 11: Summary of participants in semi-structured interviews conducted in Cotriguaçu.

Actor	Description	Number interviewed	Date of interview	Interview codes
Industries	People working in industries related to forest management for more than 20 years.	4	28/06/2022	COT1
			29/06/2022	COT2
			26/07/2022	COT10
			06/07/2022	COT13
Farmers	People working in agriculture or livestock activities with more than 20 years in the territory.	5	30/06/2022	COT3
			01/07/2022	COT6
			26/07/2022	COT8

			20/07/2022	COT9
			27/07/2022	COT11
Institutions	Represents and employees of governmental and non-governmental institutions working in the municipality	5	30/06/2022	COT4
			30/06/2022	COT5
			07/07/2022	COT7
			25/07/2022	COT12
			12/08/2022	COT14

4.2.2.1 Content Analysis: Construction of Observation Classes

The questionnaires were first analyzed using a floating reading approach to identify categories of observations. The methodology followed consisted of extracting words or phrases from the survey responses (verbatim and strictly literal) that contained information related to forest dynamics processes and any of the factors identified in the adapted Geist & Lambin (2001) model.

This information was then subjectively interpreted by the analyst in two ways:

1. Associating the responses with different semantic categories, such as climate, deforestation, legislation, etc.
2. Classifying the responses into rubrics of various typologies, covering aspects of forest dynamics, land tenure, and territorial governance.

The final number of rubrics was determined based on their mention in at least one response per site. These rubrics were then grouped into broader classes of "quotes" linked to the hypotheses.

At the end of the two phases of this content analysis, for each respondent, the following variables were recorded: (i) The number of rubrics mentioned (1 if the rubric was mentioned, 0 if not), and (ii) The number of times the respondent provided information related to each citation class.

Hypothesis H1 – Visions of the territorial dynamics

Given that each institution operates within the scope of a specific mandate, it is expected that actors will focus more closely on certain aspects of the territorial system that align with their operational responsibilities. While this does not preclude a broader understanding of territorial dynamics, day-to-day management often leads to decisions being made without a full consideration of the system's overall functioning or of the direct and indirect impacts of those decisions.

We therefore hypothesize that the types of "observations" made by actors are shaped by their institutional function and position within the territorial governance system. Accordingly, actors whose roles place them in close proximity to forest dynamics such as logging companies are more likely to report observations related to processes or proximate causes, rather than to underlying drivers or structural factors.

Hypothesis H2 – Visions of "solving problems" (governance model)

Environmental history in Brazil has been shaped by enduring tensions between deeply contrasting visions of nature. Since the 1960s, natural areas have been the target of large-scale "colonization" initiatives promoted at the national level as instruments of territorial development. Within this context, a major divide has emerged between a utilitarian approach to nature as a resource to be exploited and a normative perspective that recognizes intrinsic ecological rights.

Kroger (2016) examines how actors align with these diverging visions, revealing that environmental decision-making often reflects differentiated governance rationalities. Depending on their values, institutional affiliations, and historical trajectories, actors may favor actions grounded in agency (e.g., local adaptation, innovation) or in structure (e.g., legal enforcement, centralized planning). We therefore hypothesize that differences in governance or "solving problems" preferences particularly in how problems and solutions are defined reflect broader normative positions and contribute to the fragmentation or convergence of forest management strategies.

Two classification approaches were developed based on thematic categories, aligned with the study's hypotheses.

Classification 1: Territorial dynamics model (H01)

This classification was designed to examine H01, which hypothesizes that all actor types share a similar and comprehensive understanding of territorial dynamics. These categories in fact contain somehow governance indicators as described in the theoretical section on forest governance (4.1.2.1).

The classes for this classification are:

- Resources: Natural or economic resources mentioned in responses.
- Norms: References to legal frameworks or institutional norms.
- Opportunities: Positive aspects or potential solutions identified.
- Threats: Challenges or risks affecting forest governance.

Classification 2: Visions of “solving problems” (governance model) (H02)

This classification was used to test H02, which hypothesizes that stakeholders share similar perspectives on solving problems approaches.

The proposed classes include:

- Diagnosis: Observations on forest conditions, climate, and interrelations.
- Agency-based norms: Internal institutional policies and management plans.
- Structure-based norms: Legal regulations, laws, and governance frameworks.
- Agency-based adaptations: Institutional strategies to improve governance.
- Structure-based adaptations: Policy reforms or structural governance improvements.
- Productivist vision: Opinions and values favoring economic production.

This dual classification system allows for an in-depth analysis of stakeholder perspectives, providing insight into the alignment (or divergence) of visions across different actors involved in forest governance in Cotriguaçu.

4.2.3 Participatory Workshop in Cotriguaçu

Academic literature on forest management only partially describes the institutions responsible for managing key factors, whether in terms of decision-making, implementation, or monitoring of changes. One of the expected outcomes of the participatory workshops was to identify institutions and their interactions (or lack thereof) in territorial forest management in Cotriguaçu.

Due to actor availability, the workshop focused solely on the process of forest regeneration in Cotriguaçu. The following hypothesis was tested:

Hypothesis H02: Stakeholders share similar perspectives on solving problems approaches (here APP restoration) aligned with the territorial model of forest dynamics.

4.2.3.1 Methodology

Stakeholders were divided into two homogeneous groups based on their professional roles that are related to the institutions in charge of the forest governance. Since each group is, a priori, responsible for different factors, this allows for testing the null model H02. If the responses of the two groups are similar, the null model (H02) cannot be rejected.

- Group 1 included individuals working in the tertiary economic sector, such as public banking professionals, technical assistance providers for businesses and small-scale producers, PCI (Produce, Conserve, Include) program stakeholders, and local PCI consultants.
- Group 2 consisted primarily of agriculture-related professionals, including representatives from SEMA (State Secretariat for the Environment), the Municipal Secretariat for the Environment and Agriculture (CMDRS), the Secretariat of Education, the Rural Development Council, and a student preparing to join the PCI initiative.

4.2.3.2 Workshop Instructions for Stakeholders

The workshop was structured into four key phases, with stakeholders following the instructions below:

1. Identifying actions for restoring Permanent Protection Areas (APPs)
 - o Participants suggested necessary actions, considering human, social, political, and technical factors.
 - o Each participant wrote down an idea on a post-it note, which facilitators organized into categories of direct and indirect factors.
 - o Participants analyzed dependencies:
 - What are direct factors dependent on?
 - What additional actions are required to address these solutions?
 - o If a post-it already existed, arrows were used to indicate the type of influence (increase or decrease).
2. Assessing feasibility: can this be achieved collectively today?
 - o Blue dots were used to mark solutions that participants believed could be implemented using their available skills and resources.
 - o Red dots were used for solutions that participants felt were not feasible under current conditions.
3. Discussing challenges
 - o The group analyzed cases with a mix of "YES" and "NO" responses, as well as those with only "NO" responses.
 - o Participants reflected on how to interpret these results and identified underlying barriers.
4. Turning "No" into "Yes"
 - o The discussion focused on finding solutions to make previously unfeasible actions achievable.
 - o At this stage, facilitators introduced policy recommendations and public initiatives based on the research findings.

4.3 Results

4.3.1 Common vision of territorial dynamics model

We examine here only point 5, “Shared Vision and Common Objectives for Forest Management,” identified by EFI (as described in section 1.2); the other points must be tested with other data and protocols beyond the scope of this thesis.

4.3.1.1 Stakeholder sensitivity to the different components of the forest territorial system.

In the analysis of stakeholder sensitivity to the various components of the forest territorial system, three key types of actors are identified: industries, farmers, and institutions. Below is a contingency table that reflects the mentions of each group regarding the resources, norms, opportunities, and threats present in this system (Table 12).

Table 12: Contingency table of the three types of actors.

	Resources	Norms	Opportunities	Threats
Industries	7	5	2	5
Farmers	8	7	4	14
Institutions	12	12	5	6

The permutation test (well-suited for small sample sizes) for independence between rows (types of actors) and columns (components of forest governance) in the contingency table 3 yielded the following results:

- Observed Chi² statistic: 19.73
- Permutation-based p-value based on 10000 simulations: 0.9958

This very high p-value indicates no significant departure from the null hypothesis of independence. In other words, the distribution of responses across governance components of the forest territorial system (resources, norms, opportunities, threats) does not significantly differ among the three actor’s categories (industries, farmers, institutions).

However, qualitative analysis reveals substantive differences in perspectives and practices, which are not necessarily reflected in the statistical results. There are detailed in this section :

Resources

- **Industries** view forest resources primarily as an economic asset, particularly through sustainable management plans. They emphasize the value of non-timber forest products such as Brazil nut harvesting.
- **Farmers** arrived in search of agricultural opportunities; initial land use focused on forest clearing for subsistence crops, later transitioning to pasture establishment for cattle ranching. In recent years, they have noted soil degradation and declining water availability.
- **Institutions** emphasize resource protection and regulation, especially through the implementation of the Rural Environmental Registry (CAR) and the restoration of Permanent Protection Areas (APPs). Tensions arise between institutional conservation goals and farmers' practical needs.

Norms

- **Industries** perceive forest management norms as beneficial for long-term sustainability, and highlight the importance of institutional oversight and the ban on fire use.
- **Farmers** recognize the relevance of environmental norms but express concern about restrictions imposed on their economic activities, especially regarding bureaucracy and land-use constraints associated with CAR.
- **Institutions** acknowledge strong social resistance during the colonization period, when deforestation was a culturally embedded practice. Since 2008, legal enforcement has been strengthened, including the creation of local environmental councils and implementation of CAR. However, modifications to the Forest Code have weakened certain conservation requirements.

Opportunities

- **Industries** identify environmental services markets, particularly carbon credits, as opportunities to diversify income while maintaining sustainable forest management.

- **Farmers** consider economic incentives essential for forest conservation, and identify silvopastoral systems as promising alternatives for more sustainable livestock practices.
- **Institutions** support economic and technical incentives to foster conservation. They highlight the need for technical assistance, demonstration units, and the promotion of good agricultural practices to align productivity with environmental preservation.

Threats

- **Industries** identify illegal deforestation and fire use as major threats to the sustainability of their managed forest areas. They point to critical fire months (June to September) and changing climate patterns.
- **Farmers** mention threats most frequently, emphasizing the use of fire by neighbors, shifts in rainfall patterns, temperature increases (up to 3°C), and degradation of forest edges near pastures.
- **Institutions** highlight intentional fires (criminal arson) and the lack of human and financial capacity to enforce environmental goals. They emphasize the need for increased support to municipal-level environmental governance.

Conclusion

Although statistical tests (including the permutation test) do not show significant differences between actor types, qualitative analysis reveals important divergences in perceptions and priorities:

1. A resource-oriented economic vision among industries, centered on sustainable forest management and market-based valuation.
2. A subsistence-based and pragmatic logic among farmers, reflecting economic constraints and adaptive strategies.
3. An institutional vision of regulation and territorial governance, focused on environmental conservation, but often challenged by historical resistance and limited resources.

These findings suggest that divergence is not primarily in the thematic categories mentioned, but rather in the meanings attached to these components and the strategies envisioned by each actor group.

4.3.1.2 Cross-analysis of Structural and Agency-based Emphases (Hypothesis H02)

Table 13 differentiates between:

- Agency-based norms and adaptations, which refer to internal, localized dynamics driven by the actors themselves (e.g., mutual agreements, behavioral change, grassroots coordination).
- Structure-based norms and adaptations, which refer to external, institutions and visions of the categories of stakeholders.

Table 13: Data derived from the interviews in the “governance” section that allow us to capture the behavior, practices, motivations and visions of the categories of stakeholders

	Diagnostic s Forest/ Weather/ interaction	Norms/ rules Agency	Norms rules/ Structu re	Adaptatio ns/ Practices Agency	Adaptati ons/ Structur e	Vision s Produ ctivity	Visions Environ mentalists
Industries	17	6	9	18	12	1	8
Farmers	20	6	8	12	10	5	0
Institutions	16	5	22	18	18	5	5

To assess whether the distribution of governance-related themes varied significantly across stakeholder categories, a permutation-based chi-square test of independence was conducted on the contingency table derived from interview coding (Table 14).

Table 14: Data derived from the interviews without the «visions» to perform the statistical test

Stakeholders	Agency Norms	Structure Norms	Agency Adaptations	Structure Adaptations	Total Agency	Total Structure
Industries	6	9	18	12	24	21
Farmers	6	8	12	10	18	18
Institutions	5	22	18	18	23	40

Results:

- Observed χ^2 statistic: 8.71
- Permutation-based p-value: 0.9996

Interpretation:

The test reveals no statistically significant association between stakeholder categories and the governance types (agency vs structure dimensions). The very high p-value confirms that the distribution of emphasis on agency and structure-related elements is not different enough across actors to reject the null hypothesis of independence.

Interpretative Summary by Actor Type

Industries

Industries demonstrate a relatively balanced discourse between agency and structure. They highlight the importance of local-level organization and cooperation (e.g., landowners training neighbors, establishing agreements), while also recognizing the role of state-led incentives, environmental regulations, and carbon financing schemes.

This indicates a hybrid position, slightly leaning toward agency, reflecting their dual role as both regulated actors and proactive participants in environmental governance.

Farmers

Farmers present a perfectly balanced distribution between structure and agency. While they emphasize the need for institutional support (e.g., economic incentives, technical assistance), they also stress individual and collective capacities to adapt, especially in relation to land use practices and environmental service compensation.

Their discourse reveals a pragmatic and adaptive posture, navigating between institutional dependence and autonomous management strategies.

Institutions

Institutions are clearly oriented toward structural concerns, with significantly more references to regulatory frameworks and public instruments (e.g., CAR, Forest Code, PCI). Although they also acknowledge the importance of local engagement and capacity-building, their dominant focus remains on rule enforcement and policy coordination.

This reflects a strong structural orientation, consistent with their role as regulatory and coordinating bodies within territorial governance.

This analysis shows that stakeholder types differ not only in the number of references to governance components but also in the weight they assign to structure versus agency.

- Institutions clearly adopt a structural perspective, emphasizing legal frameworks, formal governance mechanisms, and programmatic implementation.
- Industries demonstrate a more hybrid orientation, combining references to both institutional structures and local adaptive capacity.
- Farmers display a balanced approach, reflecting a pragmatic stance that values both institutional support and individual initiative.

While certain categories are cited with similar frequency across actor types, the underlying meanings and priorities associated with these themes differ substantially.

Stakeholder Perceptions and Forest Governance Modalities in Cotriguaçu: A Synthesis

The analysis of interview data across the categories presented in Table 4a reveals a nuanced articulation of how each stakeholder group—industries, farmers, and institutions—relates to the forest territorial system, particularly in terms of agency and structural dimensions. While the distribution of agency and structure-related mentions varies quantitatively (e.g., institutions emphasize structure more than agency), the discourse analysis shows

overlapping and sometimes divergent framings of environmental challenges and governance responsibilities.

1. Diagnostics of Forest-Climate Interactions (Structure-oriented)

All three actor groups frequently mentioned forest-climate diagnostics, reflecting a shared understanding of environmental change as a structural reality. Industries noted shifts in rainfall and rising temperatures in deforested zones: “The climate has changed here as well. It used to rain day and night [...] only 45 days of dry weather throughout the entire year” (COT 13). Farmers emphasized the decline in water availability and Brazil nut production, attributing it to changes in wind and evaporation patterns. As one farmer put it: “The benefit that the forest gives us is clean water [...] most people do not pay attention to this” (COT 6). Institutions focused on the cultural persistence of fire usage and its ecological consequences: “What has changed the most over time is the relative humidity [...] one consequence of deforestation is flooding” (COT 7).

2. Agency Norms (Agency-oriented)

Industries and farmers referenced agency norms equally, highlighting collaborative agreements in forest management zones (e.g., between landowners and Brazil nut collectors). Institutions underscored the decentralization of environmental responsibilities: “Forest management is not only the government’s responsibility but also that of private landowners.”

3. Structural Norms (Structure-oriented)

Institutions were by far the most vocal on structural norms (22 mentions), emphasizing the legal constraints and limitations of the Forest Code. The quote “It created challenges because it conflicted with cultural norms [...] the legislation is heavily focused on conservation and prohibition” (COT 7) illustrates institutional frustration with legal rigidity. Industries highlighted political cycles (e.g., under Bolsonaro) that shaped enforcement intensity. Farmers recalled how older land-use policies (e.g., INCRA allotments) contributed to widespread deforestation.

4. Agency-related Adaptations (Agency-oriented)

Industries and institutions both strongly emphasized adaptations through agency (18 mentions each). Industries promoted behavioural change via pilot farms and farmer training: “In management and Brazil nut collection areas, fire is not used, and landowners educate their neighbors” (COT 2). Farmers similarly supported Payments for Environmental Services (PES) as motivational tools: “If I had income from preserving the forest, I would take care of it” (COT 6). Institutions promoted PCI strategies and technical assistance as transformative mechanisms: “Municipalities do not have enough technical staff [...] PCI brings in cooperation and resources” (COT 12).

5. Structure-related Adaptations (Structure-oriented)

Institutions again dominated this category (18 mentions), discussing CAR implementation challenges and inter institutional coordination. Farmers stressed the need for subsidies to fulfil restoration obligations: “If the government sent money to take care of the forest [...] we won’t cut it down anymore” (COT 8). Industries pushed for carbon markets and better targeting of degradation hotspots: “We are interested in carbon credits [...] 30,000 hectares available” (COT 10).

6. Visions: Productivist vs. Environmentalist (Mixed agency/structure)

Farmers leaned toward a productivist vision (5 mentions), citing the need to maintain productivity amid land-use shifts. Institutions emphasized integrating productivity and conservation through PCI. Notably, industries articulated a dual vision: environmental values—“The forest is a source of income through forest management and ecotourism” (COT 2)—and productivist imperatives. Institutions warned that the capitalist model, left unchecked, could erode ecosystem services: “If you do not use them correctly, you lose the system’s ability to sustain itself [...] our political representation is influenced by these factors” (COT 14).

Conclusion

This discourse analysis aligns with the quantitative pattern observed in Table 15: institutions are more structure-focused, while industries and farmers engage more evenly across agency and structure. However, the thematic content of their narratives highlights areas of convergence (e.g., the shared concern over water availability and fire) and divergence (e.g., visions of sustainability and restoration pathways). These differences are critical for tailoring governance indicators and decision-making tools to each actor group's priorities and operational logic, institutional frameworks or regulations (e.g., legal norms, public policies, environmental programs).

4.3.2 Results from the two workshops

Group 1 : key factors for the restoration

The first analysis group identified seven key factors comprising a total of 24 necessary actions for the restoration of Permanent Protection Areas (APPs) in the municipality of Cotriguaçu, (Fig.70).

In Factor 1: Climate Funds, two essential actions were identified: biodiversity credits and climate funds. Participants noted that these actions largely depend on the availability of external financial resources, as there are currently insufficient funds for their implementation.

In Factor 2: Sustainability, two key actions were highlighted: generating extractive income through Brazil nut harvesting and implementing agroforestry systems. Both were noted as dependent on external factors, suggesting the need for institutional and financial support to ensure their viability.

In Factor 3: Inputs, three actions were identified: the provision of fruit plants, irrigation systems for seedlings, and the operation of municipal nurseries for seed production. No significant dependencies were reported in this group, indicating that these actions can be implemented using existing resources and capacities.

In Factor 4: Projects, three essential actions were identified: developing new conservation projects, strengthening existing initiatives, and reevaluating projects that have not been executed or have failed. Participants recognized dependencies in the reevaluation of failed projects, emphasizing the need for technical and financial support to reformulate strategies and enhance execution.

In Factor 5: Public Sector Governance, ten actions were identified, focusing on legislation and public management of APP restoration. These actions include the creation of a municipal law for payment for environmental services, implementation of incentive laws, allocation of resources for fencing APPs, strengthening the public sector's commitment and involvement in environmental management, establishing a municipal restoration fund, promoting fencing by producers, enhancing technical assistance, and increasing financial investment. Dependencies were noted in the need for greater involvement from municipal secretariats, commitment from the public sector, the creation of a municipal restoration fund, and financial investment.

In Factor 6: Communication and Market Connection, two key actions were identified: securing private sector commitment to restoration and improving communication with markets to promote sustainable products. No dependencies were identified for these actions, suggesting that they can be implemented through institutional strengthening and market engagement strategies.

In Factor 7: Producer Incentives, two actions were highlighted: fostering rural producers' commitment to restoration and facilitating their access to restoration measures. Participants identified dependencies in the latter action, indicating the need to develop more accessible mechanisms for producers to integrate into restoration initiatives without facing administrative or economic barriers.



Figure 70: Conceptual framework of group 1 on the factors influencing the restoration of Permanent Protection Areas (APPs) in the municipality of Cotriguaçu.

Group 2 : key factors for restoration of the APPs

The second analysis group identified five key factors comprising a total of 21 necessary actions for the restoration of Permanent Protection Areas (APPs) in the municipality of Cotriguaçu, (Fig. 71).

In Factor 1: Awareness, six actions were identified: water quality analysis in springs and water sources, dialogue with producers to promote sustainable practices, community engagement to encourage participation in restoration efforts, organization of school workshops to raise awareness of environmental issues, reduction of waste in water sources, and allocation of resources to landowners in APPs. Participants noted that water quality analysis depends on technical and financial resources for its implementation.

In Factor 2: Financial Income, one key action was highlighted: payment for environmental services as an incentive for conservation. A dependency was

identified for this action, indicating that its implementation requires a viable financial scheme and institutional support.

In Factor 3: Investment, five essential actions were identified to ensure the necessary resources for restoration: allocation of funds for technical investments, availability of means for APP restoration, development of projects that consider restoration implementation costs, financial resources for fencing restoration areas, and reducing inequality among producers regarding their investment capacity. Dependencies were noted in financial resources for fencing and in the inequality among producers, suggesting the need for differentiated policies to support resource-limited farmers.

In Factor 4: Technical Aspects, six necessary actions were identified for APP restoration: implementation of demonstration units to train producers, availability of seedlings for restoration, definition of technical criteria for restoration, cleaning of small water sources that flow into rivers, construction of bridges to improve APP access, and planting of native or exotic species depending on ecological needs. A dependency was identified in bridge construction, indicating the necessity of infrastructure and financial investment for this action.

In Factor 5: Legislation, two key actions were highlighted regarding the legal framework and its effective enforcement: promotion of legal knowledge related to restoration and the implementation of effective monitoring to ensure compliance with regulations. No dependencies were identified for these actions, suggesting that they can be implemented through institutional strengthening and information dissemination strategies.

especially in relation to fencing, climate finance, and payment for environmental services (PES). This alignment suggests a shared understanding of the multidimensional nature of ecological restoration, which requires a combination of material inputs, governance reforms, and social engagement.

Technical Dimensions:

Group 2 developed a more detailed technical framework, focusing on the implementation of demonstration units, ecological criteria for species selection, and micro-infrastructure (e.g., bridges, water source cleaning). These points reflect an operational logic, oriented toward on-the-ground restoration implementation and capacity-building among producers.

Governance and Legal Frameworks:

Group 1 devoted significant attention to public sector governance, with ten actions centered on policy development, public investment, and institutional responsibility. This included proposals for municipal laws, incentive systems, and the establishment of a restoration fund. Group 2, while also concerned with legal aspects, focused more narrowly on legal awareness and enforcement, without addressing punitive mechanisms. Interestingly, the punitive function of environmental law emerged only in Group 1, which may suggest different experiences or representations of regulatory pressure among participants.

Economic Incentives and Dependencies:

Both groups recognized PES mechanisms as key to aligning ecological goals with local livelihood needs. Notably, participants referenced PES more frequently than direct government subsidies, highlighting a perceived preference for market-based instruments over traditional state incentives. Group 2, however, went further in identifying inequities among producers in terms of investment capacity, calling for differentiated policies to support those with fewer resources.

Unexpected Gaps and Asymmetries:

Two asymmetries stand out. First, Group 1 explicitly mentioned climate finance and biodiversity credits, while Group 2 did not, despite discussing financial mechanisms more broadly. Second, Group 2 emphasized educational and awareness-raising strategies, particularly involving youth and schools, which were absent from Group 1's contributions. These differences may reflect variations in participant profiles, professional roles, or local institutional contexts.

Conclusion

Although framed through distinct lenses, both groups converged on a shared understanding of the constraints and opportunities for APP restoration in Cotriguaçu. They emphasized key issues such as technical feasibility, financial architecture, and institutional coordination, revealing a collective vision that recognizes restoration as both a governance challenge and a socio-ecological process.

Despite slight differences such as Group 1's reference to climate funds and Group 2's mention of legislative mechanisms no major divergences emerged beyond these. Both groups examined all the major factors influencing APP restoration. Notably, Group 2 provided more detail on technical pathways and highlighted market connections, as might be expected given the participants involved.

Two points stood out: first, the mention of punitive legal mechanisms by Group 1 but not by Group 2, which is somewhat unexpected; and second, the framing of income opportunities where Payment for Environmental Services (PES) mechanisms were more prominent than direct government incentives.

Overall, the results underscore the importance of inclusive, multi-actor dialogues in shaping policy and implementation strategies. Engaging diverse perspectives not only enhances the relevance and legitimacy of restoration efforts but also ensures more comprehensive and context-sensitive solutions.

4.4 Discussion

4.4.1 Partial convergence in stakeholder perspectives

The results obtained in Cotriguaçu reflect a shared awareness among different actor groups regarding the territorial dynamics of forest cover change. However, the way in which problems arising from these changes are interpreted and prioritized varies considerably among public institutions, rural producers, and industries. While institutions tend to conceptualize threats through regulatory and policy frameworks, farmers and industries are more likely to frame them in terms of economic and operational viability. This diversity of perspectives does not preclude collaboration but poses a significant challenge to building an integrated and consensus-based vision of forest governance. Effective governance requires shared narratives, but also mechanisms that acknowledge the plurality of interests. In this regard, the findings suggest that intersectoral coordination remains limited, with dialogue spaces still poorly institutionalized. The establishment of territorial platforms may help to strengthen these interactions and foster more sustainable agreements. Such arrangements are consistent with Ostrom (2009) emphasis on polycentric governance systems, which promote adaptive, flexible responses to diverse interests and scales of action.

Partial convergence in territorial perspectives also reveals an imbalance in interpretative power. Institutions tend to dominate the formal sustainability discourse, which may marginalize more pragmatic or informal local perspectives. This finding highlights the need to recognize empirical knowledge and adaptive practices that, while not institutionalized, are integral to the strategies that producers employ to sustain their livelihoods. On the other hand, the forestry industry despite aligning more closely with institutional discourse raises specific concerns about the economic feasibility of regulatory frameworks, exposing underlying tensions between conservation goals and economic sustainability. These tensions must be addressed not only through regulation but also via participatory processes that legitimize collective decision-making. As Berkes et al. (2008) and Fischer et al. (2020) argue, effective governance must incorporate local actors as knowledge holders and

co-designers of policy. Moreover, Chhatre and Agrawal (2009) demonstrate that local engagement in forest management enhances both ecological outcomes and equity. Therefore, the challenge is not merely technical or regulatory, but deeply political and communicative in nature (Arts et al., 2014; Cash et al., 2006).

4.4.2 Emphases on institutional structures versus the flexibility of producers and industries

The findings from Cotriguaçu reveal a marked divergence in priorities and approaches between institutions, farmers, and industries. While institutions emphasize formal structures, standardized regulations, and rigid policy frameworks, farmers and industries highlight adaptive capacity, operational flexibility, and accumulated practical knowledge. This tension between normative and experiential approaches underscores a core challenge in territorial governance: ensuring that environmental policies are not only technically robust but also viable under local conditions. The gap between policy design and on-the-ground implementation can lead to noncompliance not due to resistance, but because of a lack of contextual fit. Institutions must engage more directly with local modes of organization, production, and risk management. Without such alignment, restoration and conservation strategies risk remaining superficial, with limited territorial impact. As Berkes et al. (2008) and Ostrom (2009) argue, effective governance must recognize the value of local knowledge systems and institutional diversity. Moreover, Cash et al. (2006) stress the importance of cross-scale linkages for policy effectiveness, particularly in heterogeneous landscapes like Cotriguaçu.

Moreover, the flexibility expressed by farmers and industries should not be misinterpreted as defiance of institutional order, but rather as a form of agency in response to shifting contexts, market constraints, and environmental pressures. This form of adaptability grounded in experience, experimentation, and local networks is a valuable source of innovation for land management strategies. Recognizing such agency requires expanding the concept of governance beyond mere compliance, incorporating distributed capabilities and shared learning. Accordingly, public policy instruments must include

mechanisms for dialogue, rule co-design, and contextual adjustment. Effective governance in territories like Cotriguaçu depends on achieving a dynamic balance between legal frameworks and operational realities, where rules support and enhance local capacities rather than being imposed unilaterally. Arts et al. (2014) and Chhatre and Agrawal (2009) highlight how institutional adaptability and local agency can significantly improve governance outcomes. Similarly, Fischer et al. (2019) argue for governance approaches that embed participation and flexibility within policy design to accommodate socio-ecological variability. These perspectives reinforce the need to co-produce policies that are both legitimate and implementable.

4.4.3 Opportunities and limitations of restoration instruments

The participatory workshops conducted in Cotriguaçu revealed broad consensus among various stakeholders and institutions regarding the technical, financial, and institutional requirements for restoring Permanent Preservation Areas (APPs). Adequate technical assistance, stable financing, and regulatory clarity were identified as enabling conditions. However, tensions also emerged around unequal access to incentives and the application of sanctions. While some actors viewed mechanisms such as Payments for Environmental Services (PES) as promising, others expressed concerns over insufficient funding. These perceptions of inequity can undermine the legitimacy of restoration policies and their long-term implementation. Therefore, the design of such instruments must address not only technical efficiency but also distributive justice and the effective inclusion of historically marginalized groups. As highlighted by Chhatre and Agrawal (2009), equitable benefit-sharing is crucial for fostering engagement in environmental initiatives. Moreover, participatory design increases local ownership and the chances of sustained commitment (Arts et al., 2014; Berkes et al., 2008).

Furthermore, the results confirm that restoration cannot be approached solely as an ecological process, but rather as a multiscalar political and institutional construction. The coexistence of overlapping legal frameworks, sectoral agendas, and governance levels municipal, state, and federal creates coordination gaps and institutional ambiguities. In this context, participants

emphasized the need to strengthen inter-institutional articulation and to promote more flexible, locally adapted approaches. They also underscored the importance of participatory monitoring and accountability mechanisms, without which restoration programs risk becoming merely symbolic. Consequently, beyond regulatory measures, effective restoration demands robust implementation capacities, coherent incentives, and deliberative processes that translate environmental goals into concrete and sustainable territorial transformations. According to Ostrom (2009), successful environmental governance depends on polycentric systems with nested institutions and adaptive rules. Integrating such systems requires not only technical coordination but also communicative legitimacy and capacity building at all governance levels (Fischer et al., 2019; Cash et al., 2006).

4.5 Conclusion

The analysis of forest governance dynamics in Cotriguaçu reveals a fragmented yet revealing landscape of interactions between institutions, industries, and farmers. While a shared awareness exists regarding the need to conserve natural resources and mitigate threats such as fire and drought, the interpretations, priorities, and modes of action adopted by each actor group remain differentiated. Institutions tend to frame forest challenges through regulatory instruments and formal structures, whereas productive actors farmers and industries rely more on operational flexibility, situated knowledge, and local adaptive strategies. These asymmetries reflect deeper historical roots, embedded in a trajectory of agricultural colonization, weak territorial planning, and only recent attempts to coordinate governance through tools such as the Rural Environmental Registry (CAR) and the PCI program.

In this context, the governance of forest restoration should not be approached solely as a technical matter, but rather as a political and multiscale process. The participatory workshops conducted in this study have shown that actors engage with restoration not only through concrete proposals and needs but also through distinct representations of their roles, responsibilities, and constraints. Recognizing this plurality is essential to designing legitimate, inclusive, and context-responsive restoration policies.

To address the identified fragmentation and enhance inter-institutional coordination, the development of shared and operational indicators appears as a key step. Such indicators should fulfil three core functions:

1. Be understandable and actionable for all actor groups, respecting their technical skills, professional cultures, and capacities for implementation.
2. Reflect both structural and agentic dimensions of governance, making visible the balance between formal institutional instruments (laws, programs, sanctions) and local innovations (practices, agreements, self-organization).
3. Enable a dynamic and context-sensitive monitoring of territorial trajectories particularly concerning APP restoration efforts, access to economic incentives (e.g., PES), and the quality of cross-sectoral coordination.

Based on the empirical findings, the most relevant indicators for improving forest governance in Cotriguaçu may include:

- An index of local institutional engagement, capturing the presence, articulation, and resource capacity of municipal institutions and partners.
- Indicators of participation and co-construction, such as the number and diversity of agreements established between state and non-state actors, and the frequency or institutionalization of intersectoral dialogue spaces.
- Equity-sensitive indicators of access to incentives, including dimensions such as property size, income levels, and administrative barriers.
- Ecological resilience indicators, based on measurable outcomes like APP regeneration, reduction in fire incidence, or improved ecological connectivity.

Grounded in the theoretical perspectives of polycentric governance (Ostrom, 2009), situated agency (Fischer et al., 2020), and adaptive capacity (Berkes et al., 2008), this indicator-based framework supports a shift from rigid top-down governance toward a differentiated yet coordinated model. Such an approach acknowledges the socio-ecological diversity of Cotriguaçu and the uneven

distribution of power, knowledge, and resources among actors. It creates pathways for more legitimate, effective, and locally grounded forest restoration strategies, capable of addressing both environmental goals and territorial justice in the Amazon.

DISCUSSION AND CONCLUSION

General Discussion

The point of departure of this research is the recognition that landscapes of Amazonia are dynamic socioecological systems where human and ecological processes co-evolve through complex interactions in space and time (DeFries et al., 2010; Lambin and Meyfroidt, 2010; Rounsevell et al., 2012). Archetype analysis has been a viable approach to reduce complexity by identifying recurrent patterns that link specific configurations of socioecological conditions with typical outcomes (Oberlack et al., 2019; Sietz et al., 2017). In frontier regions, such archetypes can provide an operational lens for understanding landscape change and supporting context-specific management strategies (Buchadas et al., 2022; Rodrigues et al., 2009; Václavík et al., 2013). Although more recent advances have been made, the detection of differences and similarities between territorial units and related changes in forest cover remains a methodological limitation, at least concerning the integration of deforestation, degradation and regrowth processes.

To respond to this challenge, my analysis was guided by three research questions: RQ1: How can landscape units reflecting the transformation processes of deforestation, degradation, and regeneration be stratified? RQ2: What is the relationship between transformation processes and changes in landscape structure (composition and configuration), fire dynamics and legal territorial designations? and RQ3: How can landscape change analysis help us identify indicators of forest cover change that are useful for decision making? These questions structured the analytical framework of the thesis. Based on them, I identified a typology of four archetypes of forest change and analyzed their spatial composition, configuration, exposure to fire, and alignment with legal territorial categories. This allowed for an integrated understanding of how

biophysical dynamics interact with land tenure and governance arrangements across three contrasting Amazonian territories.

The general discussion is structured into five analytical sections aligned with the research questions. First, I examine what archetypes reveal beyond traditional forest cover change metrics. Second, I explore the significance of these archetypes for development policies. Third I explore how archetypes help to understand the interplay between landscape structure, land-use patterns, fire regimes, and institutional boundaries, and how these factors shape forest transformation processes. Four, I discuss the relevance of context-sensitive indicators capable of reflecting the diversity of interests and motivations among different actors, and how these indicators can support more differentiated and context-aware decision-making and forest governance. The final section address the diagnostic potential of archetypes and the importance of adopting a territorialized and situated perspective on forest cover change analysis.

[What archetypes reveal beyond traditional forest cover change metrics](#)

The results of this study reveal that forest cover change processes in the Amazon do not follow a single pattern but instead form distinct trajectories that can be grouped into four spatial archetypes: rampant frontiers, past gradual frontiers, vulnerable frontiers, and consolidated frontiers. This typology was developed based on nine metrics integrating data on deforestation, degradation, and forest regrowth.

Through this exercise, my research contributes to addressing a major gap in the forest cover change literature namely, the lack of operational methods to characterize the complexity of deforestation, degradation, and regrowth processes (Baumann et al., 2022; Buchadas et al., 2022; Rodrigues et al., 2009). By identifying differences and similarities among landscape units and the forest cover changes they undergo, the archetype approach provides critical insights for context-specific planning and adaptive management. For example, areas classified as rampant frontiers, with low levels of remaining forest and high degradation, signal the need for urgent intervention to prevent

total forest loss. In contrast, vulnerable frontiers—despite maintaining high forest cover—require preventative monitoring to avoid escalating degradation. An additional relevant finding concerns the internal composition of each archetype in terms of remaining forest, degraded forest, and regenerating secondary forest.

My findings deepen the analytical framework proposed by Schielein et al. (2018) and the "boom-and-bust" model developed by Rodrigues et al. (2009) concerning the heterogeneity of Amazonian frontiers. The identification of four archetypes systematizes patterns that Schielein had previously recognized across eight distinct frontier types in the Brazilian Amazon (post-frontier, old frontier, new frontier, NE-settlement, N-settlement, S-settlement, high pressure, and low pressure). In his results, areas with more than 10% deforestation between 2004 and 2015 were particularly associated with the old frontier, new frontier and NE-settlement categories. The main divergence lies in the period of analysis: while Schielein emphasized the spatial reconfiguration of frontiers after 2012, our study covers the period from 1990 to 2021.

More, whereas Rodrigues documented a socioeconomic collapse following deforestation, my study not confirm the collapse phase. Rampant frontiers—characterized by high recent rates of forest loss—represent the “boom” phase, aligning with the accelerated expansion described by Rodrigues. However, consolidated frontiers—defined by historical deforestation with moderate regeneration—reflect the “bust” phase, yet show that collapse is not absolute. Taking into account regeneration allows you to better characterize the dynamic after the boom. In other words, processes of secondary vegetation recovery are occurring, as evidenced by our data from Paragominas.

My method for identifying the four archetypes differs from those proposed by Buchadas et al. (2022) and Baumann et al. (2022) by incorporating three simultaneous processes of forest change—deforestation, degradation and regrowth; whereas previous studies focused solely on deforestation. This holistic approach reveals more complex archetypes (e.g., vulnerable frontiers with high forest cover but signs of incipient degradation), which are absent

from Buchadas' typology for tropical dry forests, where only five archetypes were identified based on expert-based combinations.

My results detect differences between degradation and deforestation. For example, 51% of the vulnerable areas in Guaviare exhibited both processes. This phenomenon has been underestimated in pantropical analyses such as that of Baumann et al. (2022), which prioritized purely spatiotemporal metrics of forest loss and land use. By including forest degradation, my approach explains why deforestation and degradation are not always linked and that it is important to include degradation, which challenges the notion of "inactive frontiers" found in earlier studies.

Although my results resemble the archetypes proposed by Baumann et al. (2022), who used six frontier metrics for a regional-scale analysis in tropical dry forests, my subnational-scale analysis reveals unique spatial configurations tied to local socioeconomic contexts that are not captured at regional scales. For instance, the predominance of gradual frontiers in Paragominas—associated with fire-induced degradation and agriculture—contrasts with the emphasis placed by Buchadas et al. (2022) on fragmentation as a key indicator in dry forest systems. Additionally, my study shows that vulnerable frontiers also exhibit signs of emerging degradation, with 24% of such areas observed in Paragominas. These divergences highlight the role of local drivers—such as illegal economies in Guaviare or municipal policies in Brazil—in reconfiguring frontier dynamics, thereby limiting the direct transferability of global typologies.

The recent expansion of rampant and past gradual frontiers in Guaviare reflects a transition in forest cover use and the advancement of pastures and mosaic land use systems within a context of weak implementation of peace agreements and limited territorial planning. As highlighted by Murillo-Sandoval et al. (2023), the combination of institutional weakness, legal uncertainty, and high agricultural profitability fosters uncontrolled deforestation patterns, particularly where economic incentives outweigh the state's regulatory or enforcement capacity. Archetypes offer a more nuanced understanding of land-use trajectories and governance dynamics. Unlike deforestation rates, they

capture patterns of degradation, regeneration, and fragmentation. This allows for a deeper analysis of institutional effectiveness.

In Paragominas, the coincidence of all four archetypes bears witness to an ongoing alternation among different phases of territorial governance. The high proportion of risky frontiers is characteristic of areas in which fairly intact forests remain subject to extractive pressures such as selective logging. This environment is characteristic of areas where conservation policies and environmental incentives, such as the CAR and rural sustainability agreements, have operated heterogeneously (Bendahan et al., 2013; Soares-Filho et al., 2014). The expansion of secondary forest may be viewed as an inscrutable sign, either indicating abandonment of degraded lands or a favorable response to certain local environmental policies (Pacheco & Poccard-Chapuis, 2012; Piketty et al., 2015; Poccard-Chapuis et al., 2021).

In Cotriguaçu, rampant frontier domination implies increasing pressure on the forests with recent colonization and the expansion of cattle ranching, a trend also reported by Fearnside (2008) and Alves et al. (2021) as being characteristic of low enforcement capacity and poorly coordinated inter-institutional spaces. The low proportion of consolidated zones implies a territorial system that is being institutionalized, and whose possibilities of restoration should be supplemented with integrative policies that account for diversified land uses and stakeholder interests.

I developed a typology of frontier metrics for Amazonian tropical forests. This approach is open and flexible, and the methodology can be easily adapted to other typologies and archetypes for different applications. This work contributes to recent advances in global studies on deforestation fronts (Pacheco et al., 2021) by considering the spatiotemporal dynamics of frontiers at the subnational scale and moving beyond the mere identification of deforestation hotspots within frontier areas.

[The consequences and significance of these archetypes for development policies.](#)

The discrimination between standing forest, degraded forest, and secondary regrowth within each archetype allowed not only for the testing of their

diagnostic validity but also for further understanding of how the interplay between territorial pressure and ecological response capacity shapes transitional landscapes.

The classification in archetypes offers a valuable tool for policymakers and environmental managers, enabling territorial priority setting of restoration initiatives, deforestation containment, and environmental monitoring. By establishing where and how forest change processes occur, it becomes possible to allocate resources more strategically and effectively, thereby making it easier to implement more context-specific public policies. The archetypes also allow for the development of early warning systems based on different ecological thresholds. For instance, the degradation acceleration in vulnerable frontiers may serve as a primary indicator for preventive interventions. This comprehensive approach aligns with recommendations on adaptive forest governance in the tropics; policies and credits are necessary for reducing deforestation and forest degradation (Meyfroidt & Lambin, 2009). Last but not least, this dissertation makes a contribution to the literature on Amazonian territorial sustainability by demonstrating that complex spatial data can be transposed into operational analytical tools. This consolidates the science-practice interface, enhancing action research (science-for-policy) and facilitating the construction of agreements in territories shaped by diverse socio-environmental pressures.

The differentiation among forest cover components (remaining forest, degraded forest, and secondary forest) across archetypes and study sites offers a key tool to inform place-based strategies. The high proportion of degraded forest in archetypes such as rampant frontiers, particularly in Guaviare and Cotriguaçu, highlights areas requiring urgent intervention to prevent the transition to full deforestation; this is aligned with Von Essen and Lambin (2021) recommended interventions that focus on conserving carbon stocks, reducing GHG emissions, and slowing deforestation. In contrast, vulnerable frontiers, characterized by high percentages of remaining forest and low levels of active change, represent spaces where preventive and monitoring actions may be more cost-effective.

The distribution and composition of the archetypes provide critical insight into how deforestation, degradation, and regeneration processes operate differently depending on territorial conditions. This confirms that forest transformation frontiers are not homogeneous but rather dynamic configurations shaped by a combination of socioeconomic, institutional, and ecological factors (Fearnside, 2001; Pacheco, 2012; Schielein & Börner, 2018). In Guaviare, for instance, the presence of consolidated frontiers in older colonization zones can be attributed to the stabilization of land use through established cattle ranching systems, despite increasing pressure on vulnerable areas in the northern and eastern parts of the region. This partial stabilization aligns with findings from other Amazonian frontiers where, following an initial wave of expansion, frontier advancement slows due to the consolidation of production systems (Pacheco, 2012). Along this context, the research findings not only add to more scientific knowledge about forest change pathways but also offer effective inputs towards more legitimate, contextual, and impact full interventions at the sub national level.

Finally, it is evident that forest cover change processes do not occur independently but rather in intersecting patterns, with varying intensities and combinations across territories. Archetype-based methodology provides improved interpretation of territorial complexity and reinforces the necessity to study deforestation, forest degradation, and regeneration dynamics simultaneously (Berenguer et al., 2021; Geist & Lambin, 2002; Lapola et al., 2023; Meyfroidt et al., 2024; Vancutsem et al., 2021).

Forest Archetypes as Analytical Lenses to Examine Landscape Structure, Fire Dynamics, and Institutional Frameworks

The findings of this research reveal how the integration of landscape metrics, land-use transition analysis, and the archetype approach enabled the characterization of differentiated forest transformation dynamics across three Amazonian territories.

The results obtained through the composition and configuration of forest archetypes help to explain the underlying logic of forest transformation

processes across the three jurisdictions studied. Consolidated frontiers reflect landscapes that were transformed decades ago, where the persistence of agricultural and cattle-ranching activities has led to the stabilization of land uses. These areas have been referred to in previous studies as “old frontiers” or zones in the “intensification stage” (DeFries et al., 2004; Schielein & Börner, 2018). In contrast, rampant frontiers are characterized by accelerated conversion to pasture and mechanized agriculture, intensifying fragmentation and ecological disruption (Lapola et al., 2023; Metzger, 2002).

Landscape composition and configuration analysis in archetypes revealed clear and consistent patterns of forest change. These results confirm DeFries et al. (2009), which emphasized that land use, land cover and landscape pattern; i.e., fragmentation, patch size and connectivity—are major features that must be considered when tracing ecological change over spatial scales. Similarly, Turner (1989) showed that landscape structure, as well as patch size, shape and spatial organization, has a direct impact on ecological processes. Effective landscape management requires integrating these structural aspects to support decision-making.

Fire dynamics research revealed distinct control patterns between archetypes and study sites. The greatest burned areas were found in runaway and former gradual frontiers, particularly in Guaviare and Paragominas. In Paragominas, these fire events are directly linked to agricultural expansion, mainly through slash-and-burn (Osis et al., 2019), which continues to dominate small-scale farmer-dominated areas. Supporting these findings, Bourgoïn et al. (2021) argue that more fragmented landscapes are increasingly exposed to fire. Besides, the authors reported that between 2000 and 2018, on average, fire incidents in pasturelands were significantly larger. These patterns reflect positive interactions between fragmentation and fire regimes. Furthermore, this cycle is likely worsened by forest degradation and environmental factors such as climate change, which can amplify feedback loops around landscape fragmentation, increasing fire frequency and chronic ecological decay (Alencar et al., 2015; Laurance et al., 2011; Silva et al., 2018; Silva Junior et al., 2020).

The fire regimes in archetypes help to account for how different trajectories of land use and forest cover generate fire vulnerability. Rampant frontiers, with widespread deforestation, high fragmentation, and large-scale advancing agricultural frontiers, yield highly flammable conditions like accumulated fuel loads, exposed forest edges, and reduced ecological connectivity (Armenteras et al., 2021; Brinck et al., 2017). Past gradual frontiers, where degradation intensifies with continuous patches of forest, are as sensitive areas where fire can promote fragmentation (Alencar et al., 2006; Silva Junior et al., 2020). On the other hand, while vulnerable frontiers are still maintained to a large extent, they have been reported for the effects of fire during climatic crises, for instance, in Paragominas in 2016. This suggests that the stability of these areas is relative and may be rapidly compromised without effective preventive measures (Lewis et al., 2015; Malhi et al., 2008). The spatial distribution of fires across archetypes thus reveals a geography of risk that must be integrated into multiscale strategies for climate adaptation and mitigation (Seymour & Harris, 2019).

In Guaviare, fires reached their peak in 2018, largely in rampant frontier and past gradual frontier archetypes. These findings are consistent with the work of Armenteras et al. (2019, 2021) that demonstrated that the 2016 demobilization of the FARC created a "land rush" in the Colombian Amazon. In this context, illegal actors employed fire knowingly to convert forest to pasture. This tendency is also supported by Murillo-Sandoval et al. (2022) work in that they reported the Andes-Amazon region lost approximately 95 300 ha of forest cover between 2016 and 2020, which is the period after the peace agreement between the Colombian government and the FARC. By describing the specific territorial dynamics of each archetype, interventions can be more precisely targeted. In the case of Guaviare, typed as an uncontrolled frontier in the 2018 fire peak, policy responses need to address the control of land grabbing, real-time satellite monitoring of fire hotspots, and inter-institutional coordination that articulates environmental and security-related actions.

My study discovered that there were varying spatial distributions of forest archetypes across legal and institutional land designations. In Guaviare, forests

experiencing less anthropogenic pressure—i.e., intact forests and fragile frontiers, were most frequently located in protected areas (i.e., national parks, indigenous reserves, and forest reserves). Yet these areas are facing growing pressure, as shown by Murillo-Sandoval et al. (2023), who identified ongoing encroachment for both cattle consolidation and coca cultivation in protected areas like Macarena National Park and the Nukak Indigenous Reserve. Pastures are the dominant land use in consolidated frontiers in Guaviare, though illegal crops continue to be a chronic pressure point. Solving these twin challenges demands combined policies that enhance environmental protection while also tackling local livelihood limitations.

The structure variations and the changes in organization through the archetypes reinforce the worth of the archetype approach as a policy diagnostic tool for land use. This aligns with Oberlack et al. (2019), who established two foundational characteristics of archetypes: (1) as building blocks or case typologies, and (2) as tools for pattern recognition, diagnosis, and scenario development. Consequently, archetypes provide powerful, interpretable frameworks that support evidence-based decision-making through reusable models while enhancing policy communication.

The occurrence of forest regeneration within consolidated and rampant frontiers in Brazil can be attributed to command-and-control mechanisms such as the Rural Environmental Registry (CAR), and also land abandonment. Börner et al., (2020) reported that pressure variation across forest landscapes indicates uneven impacts of conservation interventions. Remotely located low opportunity cost land users (and hence presumably low record deforestation in the past) will be more than compensated by PES since they are most likely to possess low probabilities of enforcement. Vulnerable frontiers, in turn, represent an early stage of pressure and are critical for preventing the onset of transformation trajectories similar to those observed in the other archetypes. These patterns reinforce the relationship between transformation processes and landscape structure, which is central to the research question and the overarching aim of this thesis. They also demonstrate that spatial configuration

is both a reflection and an indicator of frontier advancement (Buchadas et al., 2022; Meyfroidt et al., 2024).

The incorporation of archetypes into different categories of territorial governance further supports the argument that forest cover transformation is not merely driven by ecological dynamics or market pressures, but also shaped by the governance regimes that influence land-use decisions. In Guaviare, for instance, the presence of degraded frontiers within legally designated forest reserves points to an incomplete governance model, where formal regulations coexist with informal and often illicit practices, such as illegal crop cultivation (Dávalos et al., 2016; Murillo-Sandoval et al., 2023). This scenario exemplifies the concept of "hybrid governance" (Arts et al., 2014), where state and societal norms overlap in conflictive ways. In Cotriguaçu, evidence suggests that an institutional mosaic, protected areas and private lands may offer more resilience, provided there is coordination among stakeholders (Guerra, 2016). Thus, the legal flow of archetypes testifies that institutional arrangements form the basis of building trajectories of transformation or conservation in Amazonian territories.

Finally, land-use transition data provide evidence that even in regions where deforestation is slowing, degradation is a dynamic and continuous process. This supports further the contention that customary measures of deforestation are insufficient to guide public policy (DeFries et al., 2010; Lapola et al., 2023). Improved knowledge about forest degradation is required, as well as spatial processes, to devise more efficient territorial governance. Having worked across various subnational jurisdictions has provided a comparative perspective that enhanced both the analytical and practical quality of this work. Exposure to different socio-environmental contexts, institutional regimes, and land-use processes made it easier to analyze how forest governance challenges and opportunities manifest differently by regions. This transnational exposure also enhanced the capacity to identify context-sensitive signals and develop adaptive strategies that respond to varied local realities. Lastly, the subnational perspective also furthered the strength and applicability of the archetype-based approach to forest landscape change.

Co-Production of Indicators and Pathways for Restoration: Lessons from Local Participation in Cotriguaçu

Qualitative content analysis of the stakeholder interviews showed large divergences among actor types in Cotriguaçu regarding sensitivity to aspects of the forest territorial system. For comparison, the result of Cotriguaçu was compared with those obtained in similar Amazonian environments (Arts et al., 2014; Chhatre & Agrawal, 2009) which expressed: people are disciplined by given rules, norms and beliefs in a society. They also agree with evidence outlined by (Nansikombie et al., 2020) the founder author weak Zambian Miombo forest governance that they lack enforcement of relevant rules (customary and formal) and governance process on the ground, particularly on land use planning, prohibition on forest use, and public participation. Cotriguaçu, conversely, though climate change, drought, and fire were issues for all groups in distinct terms. Whereas farmers communicated loss of ecosystem services through embodied experience, institutions communicated law and sustainability goals. This thematic convergence coupled with strategic divergence is designed to emphasize the necessity for multi-scalar indicators that combine biophysical and socio-institutional consideration.

Based on such studies in the Amazon and tropical regions (Berkes et al., 2008; Chhatre & Agrawal, 2009), findings at Cotriguaçu confirm the coexistence of structural mechanisms and agency-based practices within complex socio-ecological system. In highly institutionalized settings such as federal conservation units, actors tend to emphasize structural norms. In more recently settled or agrarian reform areas like parts of Cotriguaçu greater value is placed on strategies rooted in local agency. The novelty of the findings lies in the relatively balanced distribution between structure and agency (Fischer et al., 2020). It emphasizes the multiplicity of actors, connections between formal and informal practises and the rules that define governance particularly among farmers and industry representatives, suggesting fertile ground for the development of flexible co-governance strategies.

Therefore, the co-produced indicators could potentially render public policy more effective in the sense that it will deal with both territorial processes and

local agendas, as argued by Berkes et al. (2008) and Fischer et al. (2020). Based on the guiding research question, how landscape change analysis can help identify useful indicators? this structure-agency analysis shows that governance itself is a component of the landscape system and should be incorporated as an interpretive variable in monitoring strategies. The predominance of structural elements among institutions is consistent with their normative function, but it does not necessarily reflect practical effectiveness. Conversely, the emphasis on local adaptations by farmers and industries suggests that landscapes are governed through an interplay of formal rules and empirical arrangements, which supports the use of participatory methods and co-produced indicators. As noted by Arts et al. (2014) and Fischer et al. (2020), landscape governance must be understood as a system of multiple scales and rationalities, not merely one regulated by formal institutions.

The comparison of the two groups of workshops reveals thematic convergence but methodological divergence. Group 1 constructed a more institutional and regulatory framework, while Group 2 focused on technical and educational actions that reflect varying interpretations of the restoration pathways. Such differences partially explain the composition of the two groups, with farmers and technicians in one and teachers and public managers in the second group. In line with studies like Chazdon & Guariguata (2016) and Brancalion et al. (2012), that encourage the articulation of public policy and local innovation, the results confirm that multisectoral engagement increases the resilience of restoration plans and supports the development of more responsive indicators to territorial conditions. The strong emphasis on PES by both sides mirrors broader trends evident in Amazonian areas, where economic measures are increasingly taking on a crucial role.

The workshop data confirms the central thesis argument: landscape analysis is only useful for decision-making when articulated with the knowledge of local actors. The strong convergence on the role of financial incentives and technical assistance shows that, even without specialized academic training, respondents recognize the constraint of purely normative approaches and offer pragmatically feasible solutions. This supports the claims of researchers such

as Berkes et al. (2008) and Ostrom (2009), who emphasize the paramount position of traditional knowledge and collective action in forest management. The identification of gaps—such as lack of funding, barriers to policy access, and inequalities among producers, demonstrates that the challenges are both ecological and institutional, and that success indicators must reflect this complexity. Accordingly, the workshops not only validate the results of the spatial analysis but enrich them by revealing dimensions invisible in maps: trust, learning, memory, and inequality.

The findings from Cotriguaçu reveal a marked divergence in priorities and approaches between institutions, farmers, and industries. These findings corroborate Fearnside's (2008) seminal conclusion that Amazonian deforestation patterns depend crucially upon actors. Specifically, Fearnside names *grilleiros* (land speculators), sawmill proprietors, and ranchers assembling great landholdings for Amazonian investment - a dynamic contrasting with Pacheco's (2012) account of post-frontier landscapes wherein 79% of woodland landholdings are converted to agricultural use, mostly pasture. This heterogeneity of actors demands policy tools attuned to particular contexts.

This assessment echoes the general theoretical argument that forest governance is not so much a question of the presence or technical proficiency of rules, but of their effective articulation through situated agency and territorial coalitions. As much as participatory workshops revealed shared concerns among stakeholder groups, they also revealed asymmetries of visions and resources to be addressed. Based on this premise, my research substantiates that sustainability transitions require deliberative governance as well as spatialized knowledge (Ostrom, 2009; Berkes et al., 2008; Fischer et al., 2020). With the integration of geospatial diagnostics, archetype mapping, and participatory governance analysis, the present thesis makes a contribution towards the formulation of a plural and adaptive forest governance framework for tropical frontier contexts.

Contributions and Implications: Archetypes as Diagnostic Tools for Territorial Decision-Making

The primary contribution of this study lies in demonstrating that forest archetypes, by integrating the three processes of deforestation, degradation, and regeneration, serve as indicators of forest transformation and, consequently, as diagnostic tools for guiding territorially contextualized decision-making. The methodological approach developed here (Briceño et al., 2025) not only distinguishes spatial units according to their ecological trajectories but also reveals patterns of transition and fragmentation associated with different land-use dynamics, rendering visible what often remains undetected in global assessments. This differentiation unveils zones with distinct combinations of forest pressure and response, such as consolidated and vulnerable frontiers, providing a robust empirical foundation for more context-sensitive policy interventions (Lambin et al., 2003; Václavík et al., 2013).

My study discovered archetypes to be sensitive to regional history and context, illustrating how the dynamics of active deforestation, prolonged forest degradation, and early regrowth stages provide a sound basis for separating management and intervention contexts. For instance, uncontrolled frontiers, characterized by intensified primary forest decline and pasture expansion, are poles apart from risk frontiers, where forest cover is still predominant but is increasingly in danger of nascent degradation. Such a level of differentiation provides opportunities for public policies to move away from universal solutions and toward territory-specific instruments.

By enabling spatial localization and continuous monitoring of forest frontiers in transition, archetypes serve as a bridge between technical knowledge and institutional priorities. They facilitate the territorialization of restoration strategies, fire control, and economic incentives such as Payments for Environmental Services (PES), precisely because they integrate forest composition, configuration, and temporal dynamics. Moreover, they provide empirical support for building indicators that resonate with the interests of diverse local actors—an essential feature in socioenvironmentally

heterogeneous territories like Cotriguaçu, Guaviare, and Paragominas. This is key to developing differential policy: where degradation precedes deforestation, fire protection and rational use are the priority; where regeneration prevails, incentive policy and technical assistance are preferable. This integrated approach is consistent with new literature on the dynamics of tropical rainforests (Berenguer et al., 2021; Lapola et al., 2023; Pacheco et al., 2021) and contributes to translating the theory of differentiated sustainability (Oberlack et al., 2023; Václavík et al., 2013a) into practice.

Beyond their diagnostic value, the archetypes also show potential as tools for adaptive governance; when validated with local actors and cross-referenced with legal and institutional structures, archetypes become mediating elements between formal policy and existing social practices. In Cotriguaçu, for example, the overlap between rampant frontiers and agrarian settlement areas underscores the urgency of mitigation strategies aligned with land reform policies. In Paragominas, patterns of secondary regeneration within consolidated frontiers may inform forest restoration programs and sustainable production incentives. In this sense, archetypes function as reference units that can support the formulation of sectoral policies and foster territorial coherence (Arts et al., 2014; Sayer & Sunderland, 2013).

The value of this research is therefore twofold: it examines and presents a reproducible methodological tool to identify territorial markers with the use of freely available geospatial data; it also provides an interpretive focus that links such markers to intervention policy. By rendering diversity in forest trajectories visible, archetypes provide a shared vocabulary among policymakers, scientists, and residents, thereby enabling more equitable, efficient, and place-specific decision-making (Berkes et al., 2008; Fischer et al., 2020; Ostrom, 2009).

Finally, by acknowledging that Amazonian environments are conditioned by a number of interacting forces ecological, economic, legal, and climatic-this work imposes the need for multi-scalar and interdisciplinary approaches in forest change analysis. The use of archetypes as signs is not to replace traditional measures but to supplement them with a systemic and relational awareness.

Therefore, it makes concrete contributions to the building of public policies more attentive to the complexity and potential of each territory.

Study Limits

This thesis advanced the knowledge state of deforestation frontiers, forest degradation, and regeneration processes at the subnational level within the Amazon rainforest. Light shed on important aspects can fuel further research into these results. I highlight three basic areas that need to be addressed: data, description, and outlook.

A first take-off point is where data availability and quality offer an important opportunity. Frontier mapping would benefit greatly from good datasets. Additional efforts are necessary to map dependent degradation (i.e., edge effects and fragmentation; Lapola et al., 2023; Matricardi et al., 2020). Complexity is involved in mapping forest degradation and sources of degradation, generating uncertainties in the Chapter II findings, particularly in deforestation frontiers (Pacheco et al., 2021). To improve Amazonian frontiers knowledge, national databases need to be constructed integrating deforestation, degradation, and regeneration to be publicly transparent. Present reliance on international efforts leads to heterogeneity of data.

Second, new variables need to be incorporated into frontier estimation in future research. While frontier indicators have tracked spatio-temporal patterns of deforestation, degradation, and regeneration, critical variables like road density, proximity to infrastructure development, and distance to nature reserves were overlooked. Incorporating these variables will enhance our capacity to unravel relationships between forest change processes and human-driven infrastructure. Critically, such analyses must put specific biogeographies and socio-ecological systems into context using participatory approaches, addressing the socio-cultural aspects. Moreover, embracing frontier measures to enhance secondary forest monitoring has significant potential.

Third, analyses should aim to analyze causal effects, mechanisms, and outcomes of forest-cover change. Archetypes and frontier metrics in this context were employed as diagnostic metrics of subnational change.

Breakthroughs could be achieved by introducing governance variables (e.g., law enforcers' presence, land tenure regimes, corruption indices). In tropical frontiers, weak governance normally enables speculative clearing (Pacheco et al., 2021). Superimposing economic data with archetypes of causal mechanisms is another approach. This three-pronged problem emphasizes the need for interoperable typologies that wed biophysical, spatial, and institutional characteristics. Creating such frameworks will shed light on leverage points for evidence-based landscape governance.

General Conclusion

The central contribution of this dissertation lies in the integration of archetype-based spatial analysis with forest transformation processes—namely, deforestation, forest degradation, and regrowth—aiming to provide an operational framework for stratifying Amazonian landscapes. In response to RQ1, the research demonstrated that it is possible to classify landscape units into archetypes using a set of metrics of deforestation, forest degradation and regrowth. This approach enabled the identification of four distinct forest archetypes: rampant, past gradual, vulnerable, and consolidated frontiers, each reflecting specific combinations of transformation processes and forest responses. These archetypes offer a more grounded and territorially sensitive alternative to conventional land cover classifications, helping to reveal spatial patterns that remain invisible in aggregate deforestation statistics.

Building on this stratification, the research addressed RQ2 by analyzing how changes in landscape composition and configuration intersect with land use, structure, fire dynamics and legal designations. The results show that rampant and past gradual frontiers are more fragmented, with higher edge densities and smaller forest patches, which in turn correlate with higher fire incidence. Vulnerable frontiers, although still maintaining large areas of undisturbed forest, exhibit early signs of degradation, indicating latent risk zones. The relationship between transformation processes and legal designations revealed important asymmetries: even within protected areas, archetypes reflecting advanced degradation were present, underscoring the limits of legal enforcement alone. These findings reinforce the need to complement formal

territorial instruments with spatial indicators that reflect actual landscape conditions.

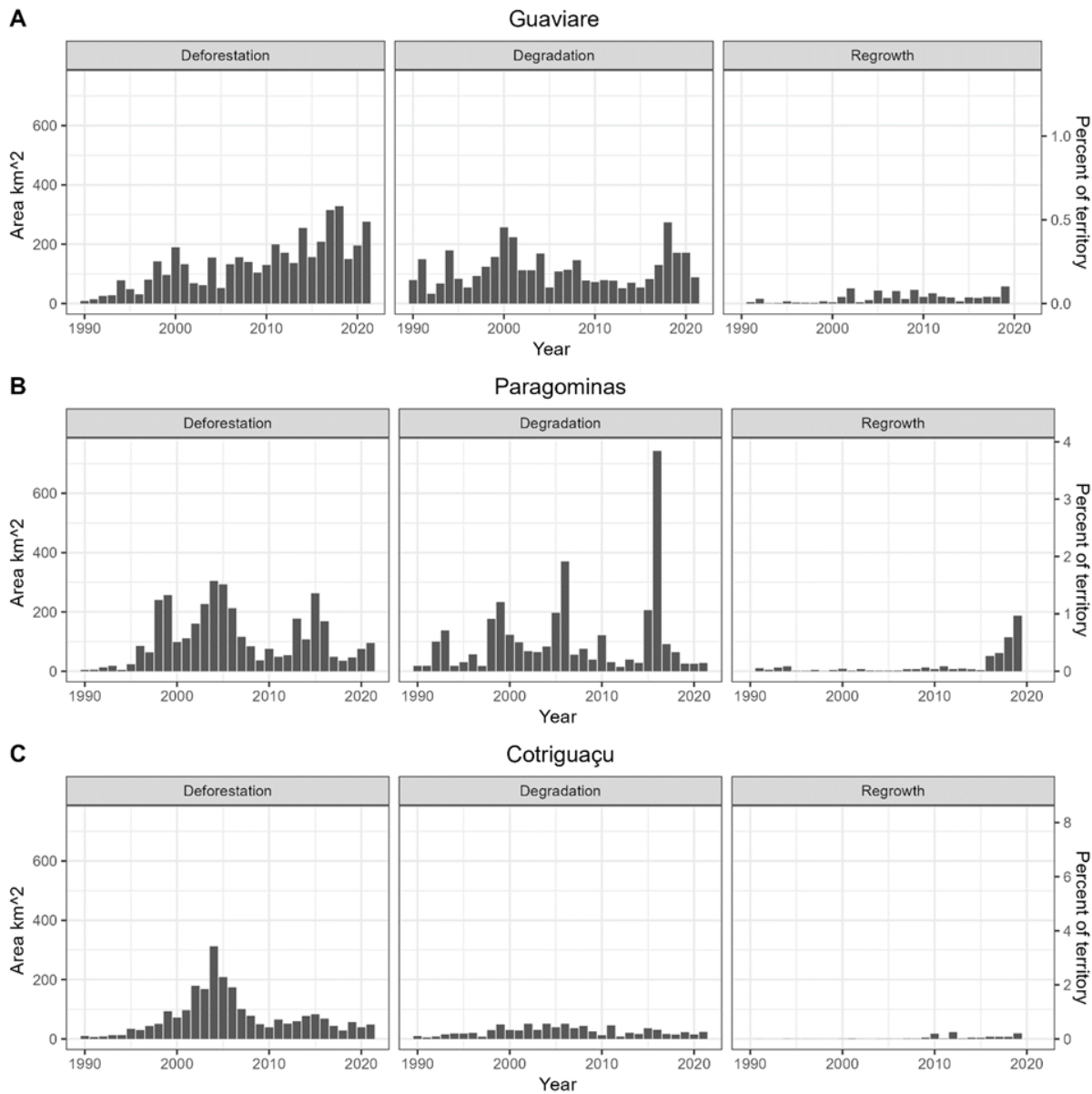
To answer RQ3, the research examined how landscape change analysis can support the identification of context-specific indicators of forest cover change for decision-making. The findings show that different actors; farmers, institutions, and industries interpret landscape signals through conflicting frames, which represent their values, incentives, and perceived risks. While quantitative analysis accounted for convergence across actor types, qualitative evidence revealed differing logics: farmers expressed adaptive pragmatism, institutions emphasized structural constraints, and industries operated under hybrid logics that combined compliance and opportunity. These differences are essential for the adaptation of governance interventions that address technical indicators to local priorities and knowledge systems.

Methodologically, the study offers an integrative paradigm that converges landscape ecology, remote sensing, and territorial governance. Rather than treating deforestation, forest degradation, and regeneration separately, the archetype framework acquires their dynamic interaction in space and time, providing a more dynamic description of forest landscape dynamics. In addition, by combining spatial data with institutional and social parameters, the study contributes to recent studies on operationalizing sustainability indicators in complex socioecological systems. This interdisciplinary integration is needed in order to create more effective, evidence-based policy that can respond to the multifaceted challenges of Amazonian forest governance.

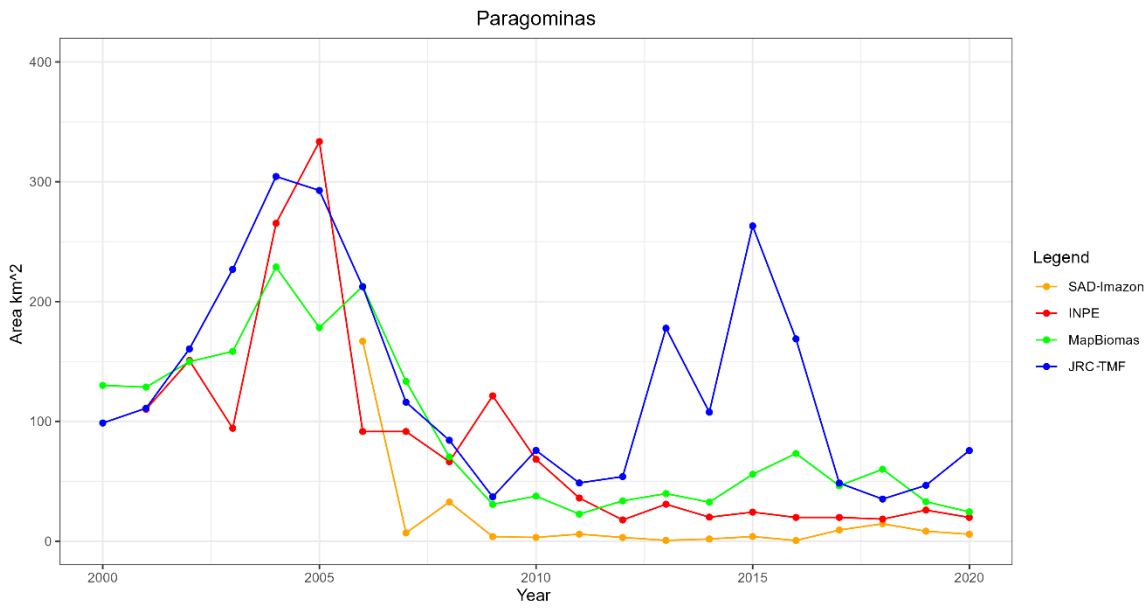
Overall, this dissertation argues that the use of archetypes as a stratification tool and indicator instrument makes forest policy more accurate and place-based. The approach improves the link between spatial knowledge and decision-making, enables the identification of critical transition thresholds, and reveals discontinuities between legal designations and ecological condition. As pressures on the tropical forests increase, tools that span biophysical processes and institutional and actor dynamics, like the archetype model developed here, will be critical in driving the evolution of more equitable, adaptive, and territorially integrated forest governance approaches.

Appendices

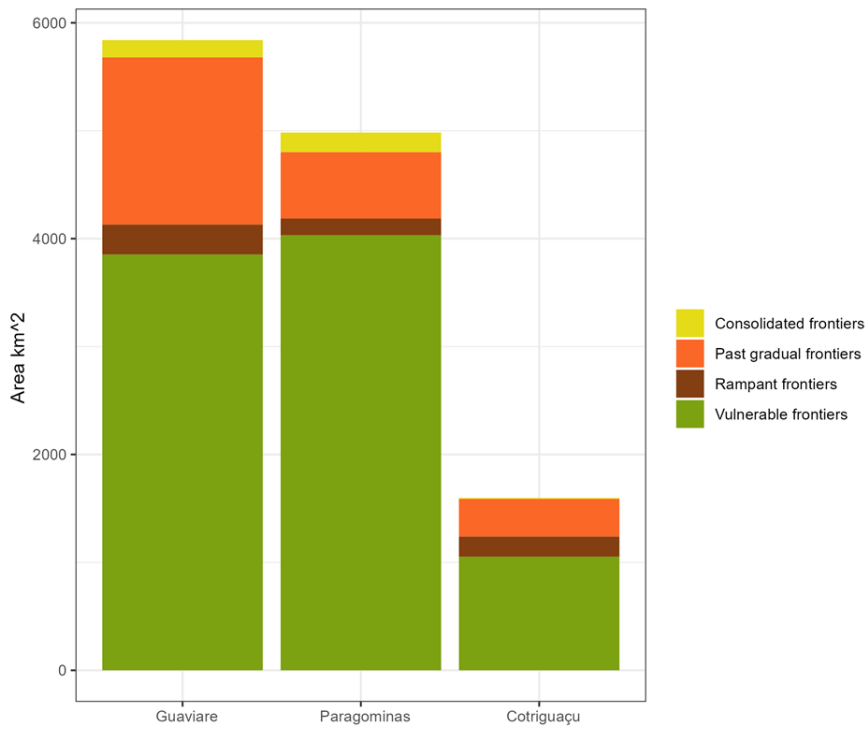
Appendix 1. Trends in annual deforestation, forest degradation and forest regrowth from 1990 - 2021, according to JRC-TMF data, at the three study sites (Guaviare, Paragominas and Cotriguaçu).



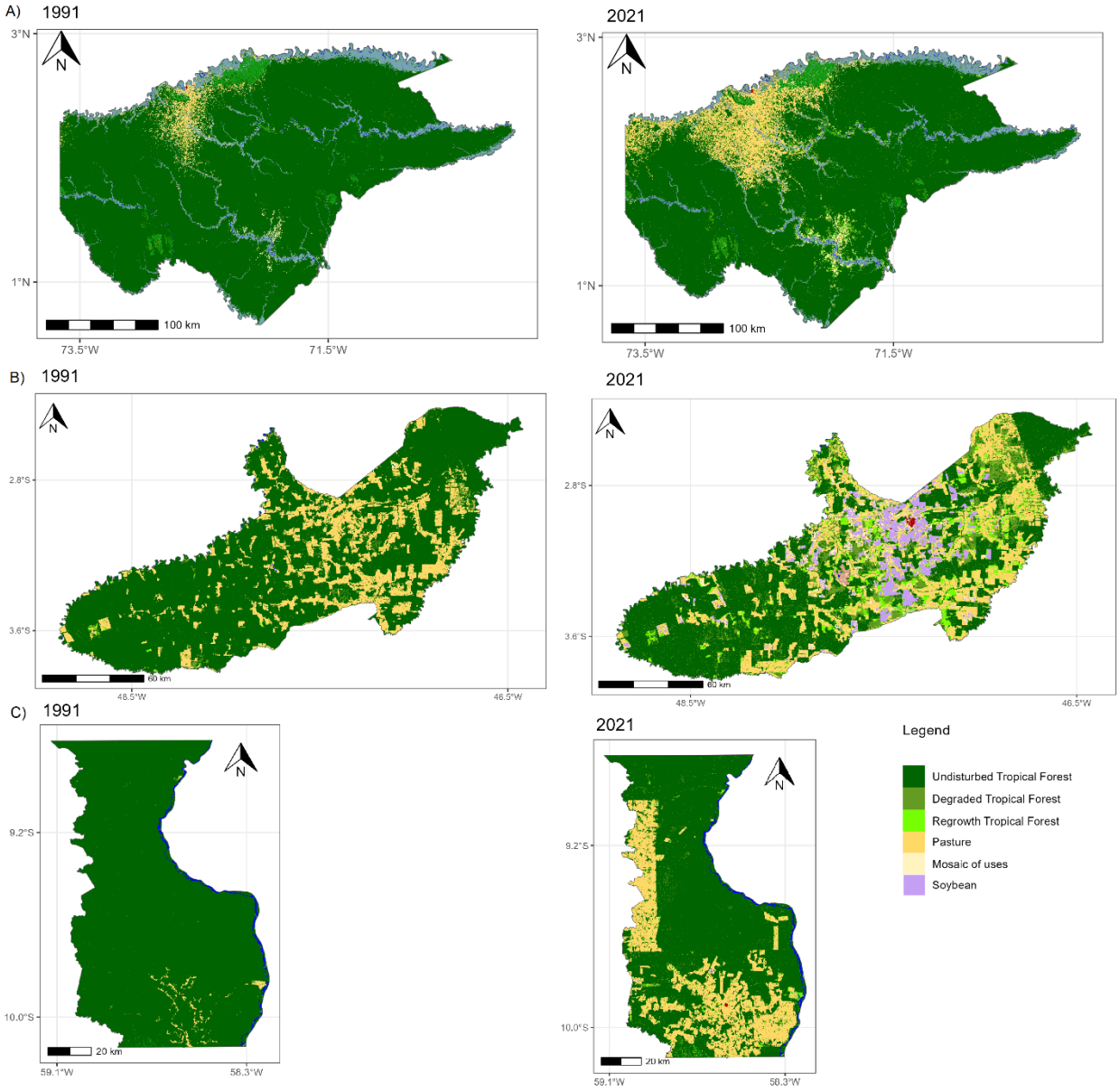
Appendix 2. Yearly deforested area in the municipalities of Cotriguaçu and Paragominas (Brazil) according to four data sources (SAD-Imazon, INPE, MapBiomas and JRC-TMF).



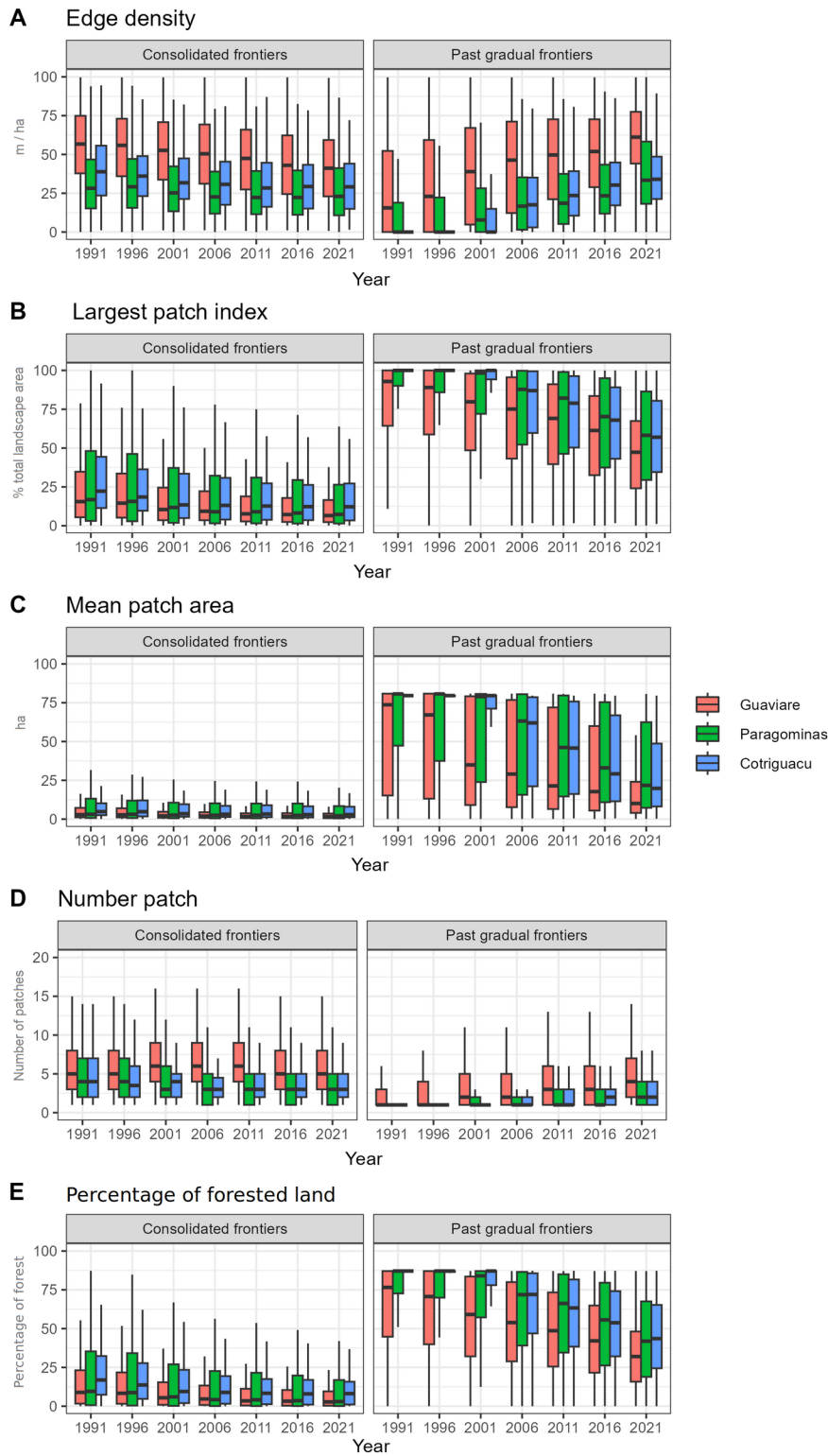
Appendix 3. Distribution of the remaining primary forests across archetypes in Paragominas, Cotriguaçu and Guaviare (2021).



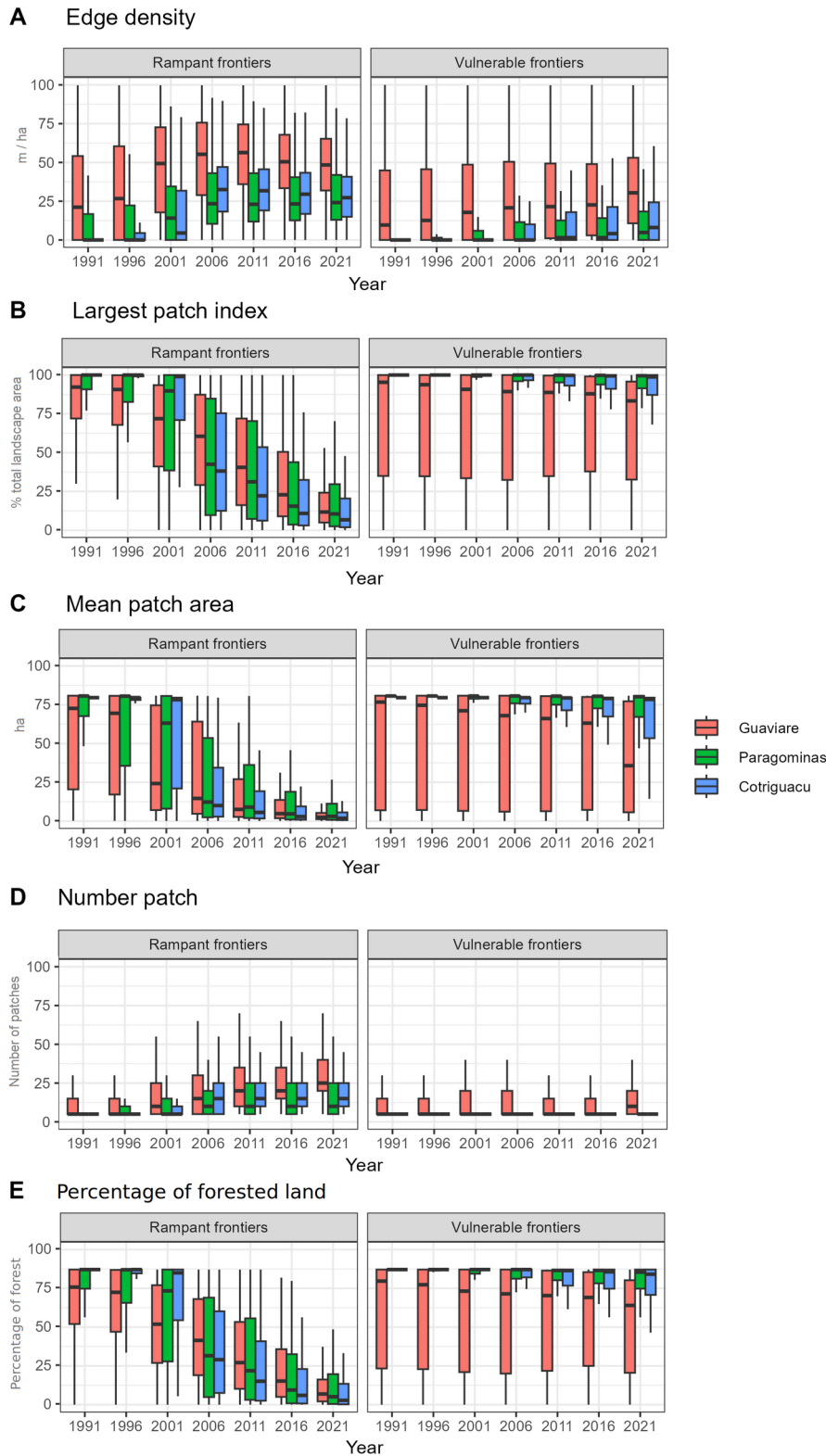
Appendix 4. Land use and land cover map for 1991 and 2021 of the three subnational jurisdictions: A) Guaviare, B) Paragominas and C) Cotriguaçu.



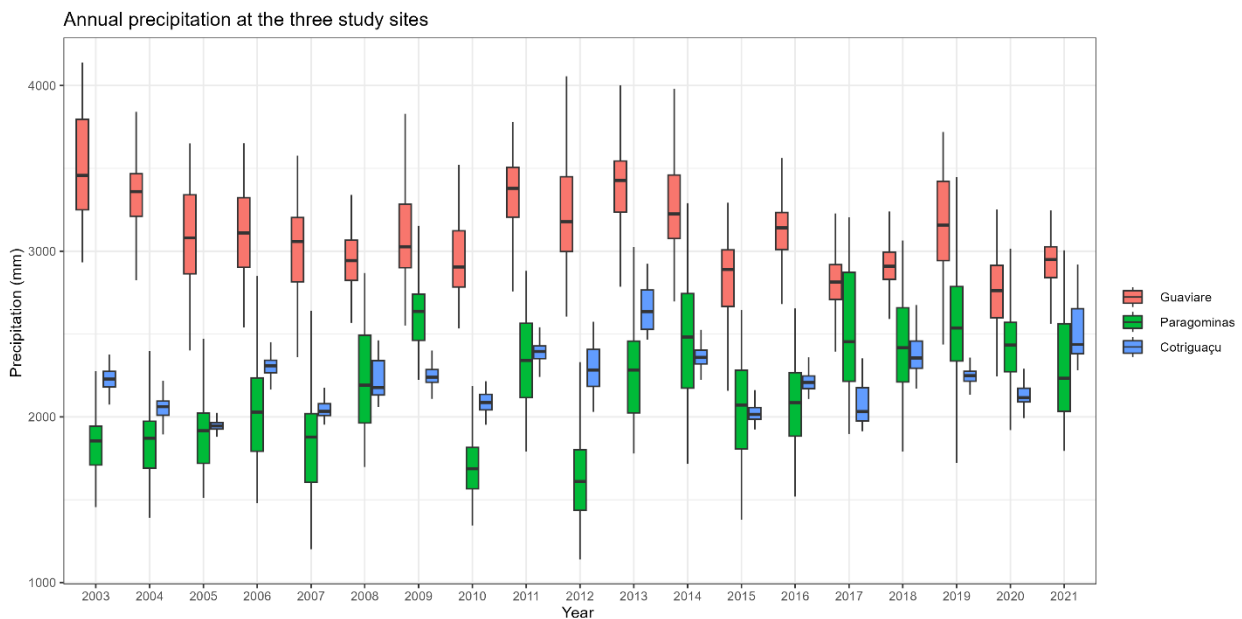
Appendix 5. Area and edge landscape metrics applied to forest patches within the consolidated frontiers and past gradual frontier with three study sites. A) Edge density; B) largest patch index; C) mean patch area; D) number of patches; and E) percentage of landscape.



Appendix 6. Area and edge landscape metrics applied to forest patches within the rampant frontiers and vulnerable frontiers with three study sites. A) Edge density; B) largest patch index; C) mean patch area; D) number of patches; and E) percentage of landscape.



Appendix 7. Boxplots of the annual precipitation for the three study sites (Guaviare, Paragominas and Cotriguaçu). Source: CHIRPS data.



Annex 1

Questions used in the 14 semi-structured interviews conducted in the municipality of Cotriguaçu

1. Who are you and what do you do? What is your role, institution, or the main activities you carry out?
2. What type of information is useful for forest management at the municipal level?
3. Are you familiar with the Terramaz project? What practical outcomes do you expect from the project for your forest?
4. Please describe the main processes and problems.
5. What are the solutions to these problems? If funding is required, how would it be used or for what purpose?
6. How should these solutions be implemented?
7. How are verification and monitoring carried out?

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Title: Dynamics of forest landscapes in Amazonian territories in transition: analysis of ecological processes and production of indicators

Keywords: Amazonia, deforestation, forest degradation, regrowth, archetypes, indicators

Abstract: Forest cover change in the Amazon is the result of complex interactions between ecological processes, institutional dynamics, and land-use decisions, leading to heterogeneous forest landscapes with varying degrees of degradation, deforestation, and regeneration. This PhD thesis aims to contribute to the understanding of forest landscape transformations at the subnational territorial scale by addressing two interrelated objectives: (i) Identifying indicators related to forest cover change will help forest cover management at a territorial scale; (ii) Evaluating how forest cover processes in the Amazon create diverse forest landscapes and the consequences. The study is guided by three central research questions: (1) How can landscape units reflecting the transformation processes of deforestation, degradation and regeneration be stratified? (2) What is the relationship between transformation processes and changes in landscape structure (composition and configuration), fire dynamics and legal territorial designations? An operational research question is also addressed: How can landscape change analysis help us identify indicators of forest cover change that are useful for decision making?. A typology of landscape trajectories was developed based on forest cover dynamics from 1990 to 2021, enabling the classification of territorial archetypes. These archetypes reflect the spatial interplay of degradation, deforestation, and regeneration and serve as a basis for assessing management priorities and informing policy interventions. Additionally, the analysis incorporated landscape structure, fire dynamics, and legal designations within archetypes by integrating multiple open-source datasets (TMF-JRC, MapBiomas, MODIS-Fire, and GLAD-Fire). Complementing the spatial analysis, participatory workshops and semi-structured interviews were conducted in Cotriguaçu (Brazil) to assess forest governance capacities. The findings show that forest cover change processes are not isolated but rather interconnected dynamics that collectively shape landscape complexity. Four distinct archetypes were identified: rampant frontiers, past gradual frontiers, consolidated frontiers, and vulnerable frontiers. Their spatial distribution highlights priority areas for restoration, fire management, and tailored governance strategies. In Paragominas, significant forest regeneration was observed, driven by pasture abandonment and transitions from pasture to regrowth, closely linked to the “Green Municipality” initiative. In contrast, Guaviare exhibited active deforestation associated with the expansion of agricultural frontiers. Cotriguaçu displayed a complex mosaic of forest degradation and intermittent fire use, shaped mainly by its colonization history. While statistical tests did not reveal significant differences among stakeholder groups regarding forest governance themes, discourse analysis uncovered critical divergences in values, capacities, and interpretations of sustainability. In Cotriguaçu, participatory mapping revealed partial convergence around restoration goals but also exposed governance asymmetries between institutional actors and local producers. This thesis highlights the importance of integrating multiscale data, archetypes-based analysis, and local stakeholder perspectives to develop governance mechanisms that are more context-sensitive, inclusive, and adaptive. It contributes to advancing emerging frameworks for territorial sustainability in tropical forest landscapes facing growing socio-environmental pressures towards a more sustainable transition.

Titre: Evolution des paysages forestiers dans des territoires amazoniens en transition: analyse des processus écologiques et production d'indicateurs de durabilité

Mots-clés: Amazonie, déforestation, dégradation forestière, régénération, archétypes, indicateurs

Résumé: Le changement de la couverture forestière en Amazonie résulte d'interactions complexes entre les processus écologiques, la dynamique institutionnelle et les décisions en matière d'utilisation des terres, conduisant à des paysages forestiers hétérogènes présentant des degrés variables de dégradation, de déforestation et de régénération. Cette thèse vise à contribuer à la compréhension des transformations du paysage forestier à l'échelle territoriale infranationale en abordant deux objectifs: (i) l'identification d'indicateurs liés au changement de la couverture forestière afin de faciliter la gestion de la couverture forestière à l'échelle territoriale; (ii) l'évaluation de la manière dont les processus de couverture forestière en Amazonie créent des paysages forestiers diversifiés et de leurs conséquences. L'étude s'articule autour de trois questions de recherche centrales: (1) Comment stratifier les unités de paysage reflétant les processus de transformation de la déforestation, de la dégradation et de la régénération? (2) Quelle est la relation entre les processus de transformation et les changements dans la structure du paysage (composition et configuration), la dynamique des incendies et les désignations territoriales légales? Une question de recherche opérationnelle est également abordée: comment l'analyse des changements du paysage peut-elle nous aider à identifier des indicateurs de changement de la couverture forestière utiles à la prise de décision? Une typologie des trajectoires paysagères a été élaborée à partir de la dynamique du couvert forestier entre 1990 et 2021, permettant ainsi la classification des archétypes territoriaux. Ces archétypes reflètent l'interaction spatiale entre la dégradation, la déforestation et la régénération. En outre, l'analyse a intégré la structure du paysage, la dynamique des incendies et les désignations légales au sein des archétypes en combinant plusieurs ensembles de données open source (TMF-JRC, MapBiomass, MODIS-Fire et GLAD-Fire). En complément de l'analyse spatiale, des ateliers participatifs et des entretiens semi-structurés ont été organisés à Cotriguaçu (Brésil) afin d'évaluer les capacités de gouvernance forestière. Les résultats montrent que les processus de changement de la couverture forestière ne sont pas isolés, mais constituent plutôt des dynamiques interconnectées. Quatre archétypes distincts ont été identifiés: les frontières rampantes, les anciennes frontières graduelles, les frontières consolidées et les frontières vulnérables. Leur répartition spatiale met en évidence les zones prioritaires pour la restauration, la gestion des incendies et les stratégies de gouvernance adaptées. À Paragominas, une régénération forestière importante a été observée, due à l'abandon des pâturages et à la transition de ceux-ci vers la repousse, étroitement liée à l'initiative « Municipalité verte ». En revanche, Guaviare a connu une déforestation active liée à l'expansion des frontières agricoles. Cotriguaçu a présenté une mosaïque complexe de dégradation forestière et d'utilisation intermittente du feu, principalement façonnée par son histoire coloniale. Si les tests statistiques n'ont pas révélé de différences significatives entre les groupes de parties prenantes en ce qui concerne les thèmes de la gouvernance forestière, l'analyse du discours a mis en évidence des divergences critiques en matière de valeurs, de capacités et d'interprétations de la durabilité. À Cotriguaçu, la cartographie participative a révélé une convergence partielle autour des objectifs de restauration. Cette thèse souligne l'importance d'intégrer des données à plusieurs échelles, afin de développer des mécanismes de gouvernance plus sensibles au contexte, plus inclusifs et plus adaptatifs. Elle contribue à faire progresser les cadres émergents pour la durabilité territoriale dans les paysages forestiers tropicaux confrontés à des pressions socio-environnementales croissantes vers une transition plus durable.