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The fate of vegetation remnants in the southern Amazon's largest threatened hotspot: part (I) a 33-year analysis of LULCC in the Tapajos River basin, Brazil

O destino dos remanescentes de vegetação no maior *hotspot* ameaçado da Amazônia Meridional: parte (I) – uma análise de 33 anos do LULCC na bacia do rio Tapajós, Brasil

El destino de los remanentes de vegetación en el punto critico más grande amenazado al sur de la Amazonía: parte (I) un análisis de 33 años de LULCC en la cuenca del río Tapajos, Brasil

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Abstract

In the present study, we evaluated the dynamics of native vegetation cover (NVC) fragmentation from 1985 to 2018 in the most threatened basin of the Rio Tapajos (TRB), a tributary of the Amazon River. The study sought to understand how land use pressures negatively impacted the remnants of the agricultural matrix and the biodiversity of local biotas. To this end, we created a sampling grid with hexagons of 50,000 hectares each, compartmentalized as follows: for the entire basin area, we used a grid of 1255 hexagons in the analyses; in the northern portion of the basin (Amazon biome), we used a grid with 965 hexagons and in the southern portion of the basin (Cerrado biome) we used a grid with 290 hexagons. In these grids, we apply six landscape ecology metrics: number, size, edge, isolation, remnants and interiority, unprecedented in landscape studies. The hexagons created were our analytical units in the study of isolation and habitat loss between forest remnants (Fo) and savannas (Sa) in the three defined Core Areas. The results showed that the fragmentation dynamics in TRB was not a single and isolated event in the three compartments analyzed, with different clusters in the studied portions. The number of remnants grew exponentially in the landscape, in the first 20 years of the study (1985- 2005), and their areas lost half their original sizes in both parts of the basin. Regardless of remnant size or typology, the edge effect was high in both small and large patches (Fo = 15% and Sa = 20%). The isolation of the remnants was greater and increasing in the northern portion of the basin, in 20 years (1985-2005), the isolation class 100 to 1000 meters increased 31% for the Fo patches, while the Sa patches increased only 11% in the southern part of the basin. The total losses of remnants (Fo+Sa) in the northern portion were 38% and 41% for the remainders of the southern portion of the basin. It is important to emphasize that this study is the largest assessment ever carried out in the entire area of an Amazon watershed, with the objective of creating a database for comparative studies with other threatened watersheds. Our analyzes showed that 60% of the TRB Plateau area was converted to planted pastures and annual crops. If the same rates of deforestation and fragmentation remain at the current level, the prognosis for 2040 will not be encouraging.

Keywords: Space-time analyses; Amazon-Cerrado biomes ecotone; Remains of threatened forests and savannas; Loss of habitats; Interiority; New landscape metrics.

Resumo

No presente estudo, avaliamos a dinâmica de fragmentação da cobertura vegetal nativa (CVN) de 1985 a 2018 na mais ameaçada bacia do Rio Tapajos (BRT), um afluente do rio Amazonas. O estudo procurou entender como as pressões de uso da terra impactaram negativamente os remanescentes na matriz agrícola e a biodiversidade das biotas locais. Para tanto, criamos uma grade amostral com hexágonos de 50.000 hectares cada, compartimentados da seguinte forma: para área inteira da bacia, usamos uma grade de 1255 hexágonos nas análises; na porção norte da bacia (bioma Amazônia), utilizamos uma grade com 965 hexágonos e na porção sul da bacia (bioma Cerrado) utilizamos a grade de 290 hexágonos. Nessas grades, aplicamos seis métricas de ecologia da paisagem: número, tamanho, borda, isolamento, remanescentes e interioridade, inédita em estudos de paisagem. Os hexágonos criados foram nossas unidades analíticas no estudo de isolamento e perda de habitats entre os remanescentes de florestas (Fo) e savannas (Sa) nas três Áreas-Core definidas. Os resultados mostraram que a dinâmica de fragmentação na BRT não foi um evento único e isolado nos três compartimentos analisados, com diferentes clusters nas porções estudadas. O número de remanescentes cresceu exponencialmente na paisagem, nos primeiros 20 anos do estudo (1985-2005), e suas áreas perderam metade dos tamanhos originais em ambas as porções da bacia. Independentemente do tamanho ou tipologia do remanescente, o efeito de borda foi alto nos pequenos e nos grandes patches (Fo = 15% e Sa = 20%). O isolamento dos remanescentes foi maior e crescente na porção norte da bacia, em 20 anos (1985-2005), a classe de isolamento 100 a 1000 metros aumentou 31% para as manchas de Fo, enquanto as manchas de Sa aumentaram apenas 11% na porção sul da bacia. As perdas totais de remanescentes (Fo+Sa) na porção norte foi de 38% e 41% para os remanescentes da porção sul da bacia. É importante ressaltar que este estudo é a maior avaliação já realizada na área inteira de uma bacia hidrográfica amazônica, com objetivo de criar uma base de dados para estudos comparativos com outras bacias hidrográficas ameaçadas. Nossas análises mostraram que 60% da área do Planalto da BRT foi convertida em pastagens plantadas e culturas anuais. Se as mesmas taxas de desmatamento e fragmentação permanecerem no nível atual, o prognóstico para 2040 não será animador.

Palavras-chave: Análises espaço-temporal; Ecótono biomas Cerrado-Amazônia; Remanescentes de florestas e savanas ameaçados; Perda de habitats; Interioridade; Nova métrica de paisagem.

Resumen

En el presente estudio, evaluamos la dinámica de fragmentación de la cobertura vegetal nativa (CNV) desde 1985 hasta 2018 en la cuenca más amenazada del río Tapajós (CRT), un afluente del río Amazonas. El estudio buscó comprender cómo las presiones del uso de la tierra impactaron negativamente en los remanentes de la matriz agrícola y la biodiversidad de las biotas locales. Para ello creamos una grilla de muestreo con hexágonos de 50.000 hectáreas cada uno, compartimentada de la siguiente manera: para toda el área de la cuenca, usamos una grilla de 1255 hexágonos en los análisis; en la porción norte de la cuenca (bioma amazónico), usamos una grilla con 965 hexágonos y en la porción sur de la cuenca (bioma Cerrado) usamos una grilla con 290 hexágonos. En estas grillas, aplicamos seis métricas de ecología del paisaje: número, tamaño, borde, aislamiento, remanentes e interioridad, sin precedentes en los estudios de paisaje. Los hexágonos creados fueron nuestras unidades analíticas en el estudio del aislamiento y pérdida de hábitat entre remanentes de bosque (Fo) y sabanas (Sa) en las tres Áreas Núcleo definidas. Los resultados mostraron que la dinámica de fragmentación en CRT no fue un evento único y aislado en los tres compartimentos analizados, con diferentes conglomerados en las porciones estudiadas. El número de remanentes creció exponencialmente en el paisaje, en los primeros 20 años del estudio (1985-2005), y sus áreas perdieron la mitad de sus tamaños originales en ambas partes de la cuenca. Independientemente del tamaño o tipología remanente, el efecto de borde fue alto tanto en parches pequeños como grandes (Fo = 15% y Sa = 20%). El aislamiento de los remanentes fue mayor y creciente en la porción norte de la cuenca, en 20 años (1985-2005), la clase de aislamiento 100 a 1000 metros aumentó 31% para los parches de Fo, mientras que los parches de Sa aumentaron solo 11% en la parte sur de la cuenca. Las pérdidas totales de remanentes (Fo+Sa) en la porción norte fueron 38% y 41% para los remanentes de la porción sur de la cuenca. Es importante enfatizar que este estudio es la evaluación más grande jamás realizada en toda el área de una cuenca amazónica, con el objetivo de crear una base de datos para estudios comparativos con otras cuencas amenazadas. Nuestros análisis mostraron que el 60 % del área de la meseta CRT se convirtió en pastos sembrados y cultivos anuales. Si se mantienen las mismas tasas de deforestación y fragmentación al nivel actual, el pronóstico para 2040 no será alentador.

Palabras clave: Análisis espacio-temporales; Ecotono de biomas Amazonia-Cerrado; Restos de bosques y sabanas amenazados; Pérdida de hábitats; Interioridad; Nueva métrica del paisaje.

1. Introduction

Landscape fragmentation and the consequent habitat loss comprise the processes that have most threatened biodiversity and ecosystem functioning in all terrestrial biomes, severely impacting native vegetation cover (NVC) and local biota (Fahrig, 2003 and 2013). It is estimated that more than 100 million hectares of tropical forests were degraded on the planet between 1980 and 2015 (Lewis et al., 2015), mainly due to the uncontrolled expansion of the agricultural frontier in these territories (Curtis et al., 2018). In the last 40 years, studies on deforestation in the transition of Cerrado and Amazon biomes showed that the impacts observed are due to the lack of a clear policy of occupation of the geographic space in the Amazon basin. Thus, there is urgency for more efficient actions in the management and land use planning (Fearnside, 2005; Nepstad et al., 2009; Nepstad et al., 2014; Souza-Filho et al., 2016; Zeferino et al., 2021).

One way to assess the consequences of fragmentation in the NVC and its effects on the ecology of local communities is through the geometric analysis of the remnants, to measure the distance between the fragments and verify their degree of isolation in the agricultural matrix (Mcgarigal & Marks, 1995; Botequilha-Leitão et al., 2006). Fragmented landscapes function as islands of isolated forest vegetation and suffer changes in their original ecological characteristics, compromising fauna and flora survival and life cycle (Fahrig, 2013). Researches in progress on occupation and indiscriminate deforestation of large territorial extensions of the Amazon basin demonstrate that there has been a reduction and isolation of the surviving fragments, which are increasingly distant from each other and the significant surrounding forest remnants (Laurance et al., 2011; Laurance et al., 2017).

This scenario of isolation and reduction of remaining landscape areas has been observed in many degraded sites of Atlantic Forest, as SE of Brazil and the South of Amazon, in the range known as the "Arc of Deforestation." Studies have shown that in these isolated forest patches, the occurrence records for some taxonomic groups of fauna are increasingly rare. These studies have drawn attention to the umbrella species (potential seed dispersers) and the top predators of the trophic chain (Norris et al., 2010; Peres et al., 2010; Boscolo & Metzger, 2011; Canale et al., 2012; Jorge et al., 2013; Bello et al., 2015; Benchimol & Peres, 2015; Antunes et al., 2016; Aurélio-Silva et al., 2016).

Redford (1992) noted that in many Neotropicals Forest fragments, large mammal species are rapidly decreasing or have become extinct, calling these sites – "Empty Forest." In the Amazon region, in addition to habitat loss, the illegal practice of deforestation, and the sneaky exploitation of wood, we still have the aggravating and recurrent use of fire in the remnants of the NVC, which further contributes to the concept of Empty Forest in these intensely fragmented areas. (Nepstad et al., 1999; Pivello, 2011; Silva Junior et al., 2018; Santos-Prestes et al., 2020; Da Silva et al., 2021; Pivello et al., 2021).

In the sizeable primary forest remnants of the Amazon, fires are rare due to the high humidity in the interior and on the forest floor (Aragão et al., 2016).

However, Nepstad et al. (1999) and Barlow & Peres (2008) showed that climate change, continuous selective removal of wood and fires to open new pastures had increased the impoverishment of the edge vegetation in these forest fragments. These three characteristics favored the recurrent outbreaks of fire spread during the dry season (Brando et al., 2014; Brando et al., 2020; Silva Junior et al., 2022). This has worsened a lot in the last decade in the Forest-Savanna transition zone, an area intensely anthropized, in such a way characterized as "Zones in the Savannah Process" (Silverio et al., 2013; Couto-Santos et al., 2014; Oliveras & Malhi, 2016; Santos-Prestes et al., 2020; Flores & Holmgren, 2021).

As a result of the advance of the agricultural frontier over forests and savannas, in 2012, Brazilian society pressured the National Congress and the Ministry of the Environment to revise the Brazilian Forest Code (BFC) (Brasil, 1965). BFC is the main technical-legal instrument that guides the control of land use, which defines the criteria for territorial planning in the six biomes and regulates the percentages allowed for the exploitation of vegetation in each national biome. According to the recommendations established in the BFC, there are four types of protected areas (PA) – Law 4,771 (1965): (1) Conservation Units (CUs); (2) Indigenous Lands (ILs); (3) Permanent Preservation Areas (PPAs – e.g., riparian forests, hilltops, slopes, etc.) and (4) Legal Reserves (LRs). These four protected areas, in addition to the areas of new vegetation (AUG) on rural properties, constitute the mosaic resulting from the anthropized NVC of the Brazilian Legal Amazon (Metzger, 2010; Brasil, 2012; Bonanomi et al., 2019).

According to the revised BFC (Brasil, 2012), clear-cutting of property (total deforestation) in the Amazon biome can occur in 20% of the NVC and the remaining 80% of the LR of the farm. In LRs, only the selective cutting of wood is allowed for the use of the rural property or forest exploitation approved by the competent environmental agencies upon presentation of the Forest Management Plan. In the Cerrado biome, clear-cutting of vegetation is authorized on 35% of the property. The remaining 65% of the area will be destined for LR, with the same technical criteria used for the Amazon biome.

Today, when we analyze the mosaic formed by the PA and AUG on the properties, we observe a picture of environmental degradation from 1980 to 2018, with many CUs, ILs, PPAs and LRs deforested and illegally occupied. These areas are dispersed within large forest massifs in the Amazon, a region corresponding to 50% (4.3 million km²) of the Brazilian territory, with complex and costly logistics for monitoring and inspection (IBGE, 2022).

Solutions to these problems remain distant and governmental actions are necessary for conserving these floristic formations and resolving agrarian conflicts in the region are still incipient (Metzger, 2010). Furthermore, the technical criteria adopted are not sufficiently robust and effective in controlling rural property licensing, monitoring, and inspection systems.

The annual increase in the rate of deforestation observed in the typologies of forests and savannas present in the Amazon and Cerrado biomes remains worrying (Fearnside et al., 2012; Da Silva et al., 2021). Fahrig (2013) stated that the high increasing rates of deforestation were intrinsically related to the dynamics of the uncontrolled fragmentation process of the NVC. This process results in an exponential increase in the number of fragments, reduction of the area of the fragments, loss of functional connectivity, increased isolation, and the consequent habitat loss in the agricultural matrix. As we move further into primary tropical forests, increasing deforestation and the number of resulting gaps, forest remnants become increasingly isolated within the agricultural matrix (Haddad et al., 2015; Stabile et al., 2020; Rosa et al., 2021).

With the increasing fragmentation underway in the Southern Amazon, the direct benefits of ecosystem services provided by the forest are compromised in the surviving forest fragments (Portela & Rademacher, 2001 and Strand et al., 2018). The increasing fragmentation is changing in situ factors such as precipitation, temperature, humidity, evapotranspiration, flood and drought pulses, seed dispersal, pollination, and fauna recruitment (Grimaldi et al., 2014; Joly et al., 2014; Scarano & Ceotto, 2015; Rochedo et al. 2018; Leite-Filho et al. al., 2021). Furthermore, degradation caused by habitat fragmentation in the occupied landscape is easier to measure and analyze, while its effects on the quality of forest ecosystem services are more challenging to measure (Fearnside, 2008; Ewers et al., 2011; Junk, 2013; Barros & Albernaz, 2014; Edwards et al., 2014; Ferraz et al., 2014; Haddad et al., 2015).

The Tapajos River Basin (TRB) is a right-bank tributary of the Amazon River with different floristic formations typical of the Amazon and Cerrado biomes. Due to the compartmentalization between these two biomes, the basin is subject to two regulations within the BFC (Brasil, 2012). This legal peculiarity creates difficulties in the field, compromising the inspection of rural properties (Metzger, 2010). It is common to see patches of diffuse savannas on many farms on the Tapajos River within a more prominent feature of the Ombrophilous Forest (Haffer, 2008; WWF Brazil, 2016; Sano et al., 2019); these phytophysiognomic characteristics end up confusing the interpretation of the Law. For a farm located in the Amazon biome with savannas patches amidst the dominant matrix forest, which criterion should adopt by the government agency in the licensing of property: an establishment for the Amazon biome of the clear-cut allowed in 20% of the property or established for the Cerrado biome of clear-cutting 35% of the property. It is a controversial technical criterion.

As you can see, these are complicated technical decisions and all with a medium-term solution, considering the remote sensors used today to monitor the NVC. The result of this technological limitation is observed in the licensing of large agricultural and livestock farms in the South of the Amazon. The owners seek the artifice of using several deforestation licenses within the same required area and, in this way, obtain authorization to deforest 35% of the rural property, as if the farm was in the Cerrado biome (Skidmore et al., 2021). Evidently, this process is questionable and has generated several conflicts between farmers and the environmental agencies responsible for monitoring and controlling deforestation in the Amazon (Macedo et al., 2012; Brandão-Jr. et al., 2020; Souza Jr. et al., 2020).

The use of raster images generated by satellites of the LANDSAT series with a pixel of 30 meters does not have the necessary spatial resolution to elucidate these specific issues of the Amazon NVC. Therefore, it is increasingly required to use new optical sensors with a high spatial resolution for the analysis of these cases of Amazonian Forest typologies; these technical issues end up being a complicating factor in the environmental licensing process of rural properties (Lu et al., 2015; Almeida et al., 2016; Grecchi et al., 2017; Tyukavina et al., 2017). In the present TRB fragmentation research, we also found limitations imposed by the low spatial and radiometric resolution of Landsat TM 5 and ETM+7 sensors. In many rasters analyzed, we found problems with the interpretation of NVC physiognomies (Overbeck et al., 2015; Silva Junior et al., 2019; Souza Mendes et al., 2019).

Strassburg et al. (2017), Latrubesse et al. (2017), and Brando et al. (2019) drew attention to the rapid changes in the LULCC underway caused by uncontrolled deforestation, recurrent fires, the opening of pastures, illegal logging, annual crops, and construction of hydroelectric dams as the main threats to Amazonian territories with huge losses from the NVC. Therefore, understanding how forest loss directly impacts the megadiverse Tapajos-Xingu hotspot is one of the first steps toward knowing how much habitat needs to be preserved in the landscape in a way that does not compromise biodiversity and ecosystem services (Fearnside, 1999; Tscharntke et al., 2005; Haines-Young & Potschin, 2010; Melo et al., 2013; Maes et al., 2016). Therefore, it is expected that fragmentation of the southern portion of TRB (Cerrado) began earlier than that of the northern portion (Amazon), since evolution of the dynamics of land use and occupation in this portion has been installed earlier than in the Amazon biome of the TRB. In aditon, both portions of basin, more than one event of landscape fragmentation occurred during the interstice from 1985 to 2018; due to periods of relaxation in environmental surveillance and the natural regeneration of the NVC.

Thus, the main objective of the study was to analyze how the spatio-temporal dynamics of the LULCC impacted the NVC in the dynamic contribution area of the TRB, within the 03 Core-Areas defined in the study from 1985 to 2018. For this, we focused on analyzing how the Fragmentation directly affected the remaining forests and savannas in the entire basin area and in the Northern and Southern Portions of the basin, areas related to the domains of the Amazon and Cerrado biomes, comprised within the basin area. By measuring the level of isolation and loss of habitats among the remnants of the NVC in the three Core-Areas analyzed of the TRB.

2. Methodology

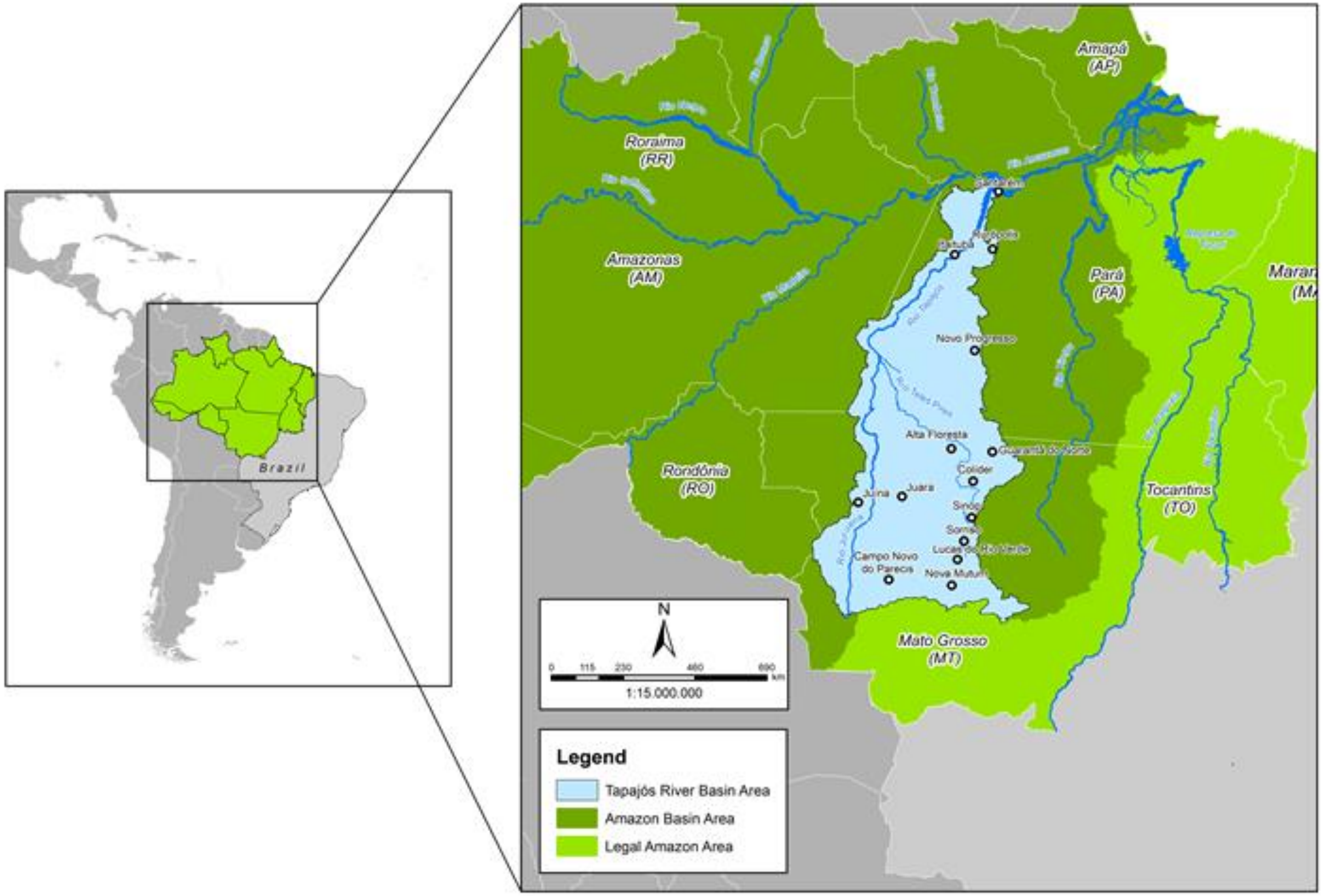
2.1 Study area characterization

2.1.1 Tapajos river basin

Tapajos and Xingu river basins comprise the most extensive transparent water system in the Continental Amazon and together represent the most prominent regional biodiversity hotspot, with unique and little-known ecosystems of rivers that drain the Brazilian Shield (Sioli, 1984; Junk, 2013). TRB was one of the first occupied and is considered the most threatened in the Legal Amazon, with high rates of deforestation and fragmentation of the NVC in the last 40 years (Davidson et al., 2012; Petry et al., 2019). Due to its sizeable territorial extension, two morphoclimatic domains (Amazon and Cerrado biomes) are included within its dynamic contribution area. These physiographic characteristics give it unique optical, hydrological, and physicochemical properties, contributing significantly to the diversity of forest formations found in seasonally flooded Igapos, Terra-Firme Forests, and Savannas on the TRB (Sioli, 1984; Ab'Saber, 1977).

TRB (Figure 1), the most important and studied clear water sub-basin on the right bank of the Amazon River, has been intensively explored since the end of the 16th century. However, several towns and cities were created in the 20th century due to the activity of gold mining, rubber exploration, and, more recently, the construction of hydroelectric dams (Becker, 2005; Schuber & Moraes, 2015; WWF Brazil, 2016). The last 40 years was the period in which the most significant and fastest changes in the NVC were observed, which resulted in high fragmentation of the original landscapes converted into planted pastures, soybean crops, and human settlements (Davidson et al., 2012; Petry et al., 2019).

Figure 1 - Contextualization of the Study Area in the South American Continent – The Tapajos River Basin, the 5th most threatened hydrographic sub-basin in the Brazilian Amazon.



Source: IBGE (2022) and IGISMAP (2022).

The upper Tapajos River intersects in its upper course landscapes predominantly formed by tall arboreal savannas (Cerradões), submontane seasonal forests, and shrub savannas (Typical Cerrado). This stretch is included in the plateau relief of the basin, where these covers are extensively fragmented, with about 40% of the area converted into farms for soybean, corn, and cotton plantations (Davidson et al., 2012).

In the depression of the basin, extensive forest massifs can be observed, formed by seasonal semideciduous and submontane deciduous forests. These formations began to be more intensively occupied from the 2000s onwards, and that is why today we still see many areas of the middle Tapajos with coverage in good conservation status. On the other hand, in the Lower Tapajos River Plain, we observed an older fragmentation process, especially in cities and towns founded in the 17th, 18th, and 19th centuries, with few deforested areas restricted to the surroundings of urban areas.

With the beginning of the 20th century, the Tapajos plain began to occupy many parts of the basin and more intensely with rapid changes in the NVC, from 1980 onwards. The advance of fragmentation is observed in several features of the relief of the plain, such as on the slopes of the hills dominated by dense and open ombrophilous forests and, in the valley bottoms, by seasonally flooded igapo forests. This scenario of the lower Tapajos has been changing rapidly after the 2000s, with the effective entry of soybeans crop and the furtive exploitation of hardwoods (Junk, 2002; Soares-Filho et al., 2006).

The authors Fearnside (2001 and 2017) and Smith (2020) warned that the indiscriminate use of TRB lands would cause significant losses to the NVC and compromise ecosystem services. Furthermore, the studies showed that the occupation without regional planning of the micro basins and tributaries of the Tapajos River would initially impact the plateau areas and later advance on the depression and lowland landscapes of the basin. The prognosis made by the authors is confirmed by the reality of the current scenario observed in the basin in 2020.

2.1.2 Morphology and hydrobiogeochemistry of the basin

The TRB (Figure 2a) is the fifth-largest Amazonian sub-basin and is 2,700 km long, between its headwaters in the south of the State of Mato Grosso and its mouth in the city of Santarem, in the State of Para, comprising an area of dynamic contribution of 764,183 km² with an average flow of 12,800 m³.sec-¹, and is distributed in the territories of Mato Grosso, Rondonia, Amazonas and Para. However, more than 90% of the basin is located between the states of Mato Grosso and Para (Petry et al., 2019).

The Continental Amazon Basin is formed by a complex and unique hydrographic system, giving rise to a drainage system with rivers of water with optical characteristics: white, clear, and black, giving the basin one of the greatest in situ biodiversity on the planet (Sioli, 1984). The area of the Amazon basin is the most significant contribution area on the earth, with an extension of 6.1 million km² and an average flow of 209,000 m³sec⁻¹ (Goulding, 1980). Among the tributaries that form the Amazon River, the Tapajos sub-basin is formed by a typical oligotrophic transparent water drainage system, which intercepts heavily leached terrains from the Cambrian period in the Brazilian Shield (Sioli, 1984; Junk, 2013). These associations between hydrological, geological, pedological, and floristic characteristics resulted in unique biodiversity in southeastern Amazonia, giving rise to important fluvial-lacustrine biogeographic ecoregions found on the TRB (Abell et al., 2008; Petri et al., 2019; Feow, 2022).

2.1.3 Land use and changes in native vegetation cover

A recent study by Zimbres et al. (2017) showed the sudden changes in land use in the period 1980-2015 in southern Amazonia, where more than 1.5 million hectares were rapidly degraded in the Arc of Deforestation, especially in the Tapajos-Xingu interfluve. Although there are still continuous forest massifs with thousands of hectares in the Depression and Plain of the basin, many savanna and forest relicts have been lost and converted into planted pastures and annual crops (Radambrasil, 2022; Zimbres et al., 2017).

It is estimated that about 10% of the soy traded today comes from TRB (Aprosoja, 2019). On the other hand, a production of this magnitude caused negative impacts on large territorial extensions to the remaining NVC, increasing the fragmentation and generating the isolation of habitats within the basin. Amazon deforestation data show that 75% of the deforested areas are in the intensely fragmented range of the deforestation arc, and many of the new open clearings are in the lower reaches of the Tapajos basin (Domingues & Bermann, 2012; Zimbres et al., 2017). In addition to soybeans, other crops contribute to the current fragmentation of the basin, such as the intercropping of soybean rotation with corn, cotton, millet, rice, sunflower, and sorghum. These cultures interface with extensive livestock and logging in the remnants of secondary and primary forests, constituting the model of the Amazonian agroecosystem (Malhi et al., 2008).

In the Plateau region, in the upper Tapajos in the south of Mato Grosso, on the tops of hills and slopes, typical savannas formations of the Cerrado stricto sensu predominate. On the slopes of plateau reliefs, submontane semideciduous seasonal forests dominate the landscape, and on the valley's floors and gallery forests, these covers are dominant in the Parecis plateau region (Radambrasil, 2022). Some of these areas were opened 50 years ago and initially converted into pastures planted for extensive beef cattle. Today, this scenario has changed almost entirely for crops with high technology incorporated into soybean, corn, and cotton. Undoubtedly, this increased productivity of the basin plateau crops has come at the expense of significant landscape changes, with more than 40% of the NVC deforested and the remnants fragmented and very isolated (Pires et al., 2016; Bolfe et al., 2020).

The NVC in the depression of the Tapajos basin comprises open ombrophilous forests with Cerrado stricto sensu enclaves in the flatter reliefs, seasonal deciduous forests, and dense arboreal savannas on the tops of hills and, at the bottom of the valleys, gallery forests (Radambrasil, 2022). The predominant use in the middle section of the basin is still extensive cattle ranching with low technology and large tracts of forests converted to planted pastures and, more recently, to a lesser extent, soybean farming (Fearnside & Laurance, 2004; Laurance et al., 2004). The depression is currently considered the second most threatened and fragmented basin stretch, with increasing losses from the NVC between 2000 and 2020.

Although cattle ranching has been consolidated for 50 years and soybean farming has had an expressive growth since 2010 in the lower Tapajos, the plain is the most preserved section of the basin. There are still extensive patches of non-fragmented forests, with thousands of km² of intangible vegetation (Figure 2b). However, this basin stretch has been occupied very quickly and with the highest NVC losses in the entire Legal Amazon (Pires et al., 2016).

Tapajos plain is the most diversified NVC of the entire TRB. Many patches of typical Amazonian "Terra-Firme" forests in the higher parts of the relief are characterized by dense and open ombrophilous forests, seasonal forests, buritis palm trees, and savanna enclaves of the Cerrado biome. In addition, we find seasonally flooded igapo forests at the bottom of the valleys associated with the gutters of the large drainages (Radambrasil, 12022).

2.2 Transition of Cerrado-Amazon biomes

One of the great Amazon basin's most outstanding characteristics is its hydrographic sub-basins physicochemical properties and floristic diversity (Sioli, 1984). Three major tributaries on the right bank of the Amazon: Tapajos, Xingu, and the Tocantins, are rivers typically formed by clear, transparent waters and very poor in dissolved nutrients, with their headwaters originating in the Brazilian Shield, intercepting ancient and leached lands from the Cambrian period (Ab' Saber, 1977; IBGE, 2022). The physical characteristics of these three sub-basins and their headwaters in the Cerrado biome give these drainages ecotonal environments with high biodiversity and endemism in the Southern Amazon.

Therefore, TRB, due to the large territorial extension of the basin, with its headwaters located on the Parecis Plateau and its mouth in the lowland of the floodplain Amazon River, is comprised of the two largest Brazilian Morphoclimatic Domains – Cerrado and Amazon biomes (Figure 2c). Because of these associated characteristics, it is included in the largest megadiverse hotspot in the Tapajos - Xingu interfluve (Ab'Saber, 1977; Myers et al., 2000; IBGE, 2022).

The following differences mark this strong compartmentalization observed in the Tapajos basin: (1) Precipitation – while at the headwaters, it rains 1400 mm.year-¹ and at the mouth, it rains 2800 mm.year-¹; (2) Hydrology – different fluviometric behaviors between the Plateau and Plain rivers; (3) Relief – significant altimetric differences between the extensive plateaus in the south of the basin (900 m) and the lowlands of the floodplain at the mouth of the basin (60 m); (4) Soils – ranging from red-yellow latosols to hydromorphic soils; (5) Landscape – high phytophysiognomic diversity, from typical savannas on the plateau to terra-firme forests and igapos in the lowland basin.

These floristic interfaces, high seasonality between the flood and drought pulses and different aquatic biocenoses between the headwaters and the plain are determinants of the high in situ biodiversity found in the Tapajos River basin (Vannote et al., 1980; Sedell et al., 1989; IBGE, 2022; Hopkins, 2007; Haffer, 2008; Junk et al., 2013; Grill et al., 2019).

Cerrado biome corresponds to a narrow strip in the south of the basin and is defined by a boundary line that cuts the basin in an east-west direction, varies between 100 and 250 km in width, and comprises the drainage areas from the headwaters of the upper Tapajos river. This stretch is characterized throughout its length by savannas typical of the Cerrado Lato Sensu biome.

The boundary of the biomes within the TRB is delimited by the black line that divides Cerrado from the Amazon (see Figure 2c). From this separation, the Amazon extends north for 2300 km to its mouth in the lower Amazon. Within the Amazonian compartmentalization of the basin, we found many patches of savanna relicts dispersed in the larger feature dominated by ombrophilous forest. Many of these savannas are threatened due to intense land-use pressure in the north of the basin (De Carvalho & Mustin, 2017; IBGE, 2022).

2.3 Regional conservation hotspot

Myers et al. (2000) and Mittermeier et al. (2004) listed 25 biodiversity hotspots distributed across five continents, one of which is in the Cerrado biome, the only site in the entire Brazilian Legal Amazon. Later, other authors corroborated the idea of new regional hotspots, where they highlighted the importance of the TRB headwaters being very close to the hotspot proposed by Myers et al. (2000) in Brazilian Cerrado (Silva & Bates, 2002; De Carvalho & Mustin, 2017; Strassburg et al., 2017). On the other hand, Morrone (2017) identified an important Biogeographic Province in the interfluve of the Tapajos-Xingu basins, reinforcing the importance of the megadiverse TRB hotspot. More recent studies on the zoogeographic distribution of birds, fish, and phytophysiognomic formations in Cerrado and Amazon confirm that the south of the basin comprises an important fluvial-lacustrine zoogeographic ecoregion (Abell et al., 2008; De Carvalho & Mustin, 2017; Morrone, 2017; Feow, 2022).

2.4 Multi-temporal maps of land cover and use

We used a set of eight raster maps of land cover from 1985 to 2018, with five-year intervals between analyzed scenes covering the entire TRB. The rasters are made available to the public by MapBiomas Institution at the link: https://mapbiomas.org/, which identified and ranked 34 land use classes at a nominal scale of 1: 50,000 obtained from the images of the satellites of Landsat TM5 series and ETM+7, with a spatial resolution of 30 meters on the ground. Although there are scenes of the basin before 1985, MapBiomas recorded and processed information on land-use changes only from

1985 onwards. Thus, we consolidated our basin database in March 2019. However, MapBiomas has made only a series of collections available to the public until 2018 – Collection 4.1.

To organize our TRB database, we used Google Earth Engine (GEE) tool is available on the MapBiomas platform. Through it, we managed the files in selected raster formats downloaded from the platform, as suggested in the articles by Wang et al. (2019) and Souza Jr et al. (2020). The great advantage of GEE is to facilitate the management of the information available in MapBiomas directories, where you can change the result of the data layers, assemble the raster you want to work with, or even directly change the tool's native Python script in the command lines. This mechanism is explained in GEE tutorial, accessible at the link: https://www.google.com/intl/ptBRbr/earth/outreach/learn/introduction-to-google-earth-engine/#homepage.

2.5 Database

All our raster files from the 4.1 collections (MapBiomas) up to the base year 2018 and the vector files used in TRB geospatial study were georeferenced and saved in ArcGIS Pro geodatabase - version 2.6. MapBiomas makes the files available and ready for use, not requiring any adjustment for the typologies of use created. This feature avoids problems with incompatibilities between different cartographic scales by simply adjusting the raster coordinate system according to the geographic dimensions of the chosen study area. For example, available raster files of the basin area in the coordinate system GCS 4326, datum WGS 84, and the present study were transformed to the projected coordinate system Albers Conical, SIRGAS 2000, due to the large dimensions of the TRB area.

This coordinate system reprojection procedure was performed in ArcGIS Pro, v. 2.6 and applied to the eight raster files (1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2018) and vector files of the CU, IL, PPA, LR, hydrography, infrastructure, urban centers, and cities. Subsequently, 34 use classes mapped by MapBiomas were rearranged and regrouped in ArcGIS into just 04 use classes, aiming at the interest of the study: Forests, Savannas, General Use, and Water Bodies. The already georeferenced files needed to study the changes in the Tapajos NVC were later saved in the geodatabase and exported to Grass-GIS to analyze landscape metrics.

2.6 Data analysis

In the analytical study on the LULCC changes in the Tapajos river basin, the criteria of geomorphological compartmentation, physiographic conditions, and morphoclimatic characteristics of the biomes comprised within the basin area were considered, thus 03 natural core areas were identified in the study (Ab'Saber, 1977; Radambrasil, 2022; IBGE, 2022), they are:

I - The entire area of the basin;

II - The northern portion of the basin, referring to the polygon that comprises the area of the Amazon biome within the basin;

III - The southern portion of the basin refers to the polygon that comprises the area of the Cerrado biome within the basin.

For the analysis of the remnants of the NVC in these 03 core areas, a sampling grid with 1255 regular hexagons with 50,000 hectares each was created in the entire area of the basin, like the methods used by Birch et al. (2007) Barreto et al. (2010) and Amaral et al. (2019), as shown in Figure 2d.

The hexagonal sampling units were decisive in the study of the fragmentation and isolation of forest and savanna remnants in the entire basin area and the northern and southern portions of the basin, dividing the hexagon grid as follows:

(a) to calculate the fragmentation metrics of the total remnants in the entire basin area, we used the complete grid of 1255 hexagons;

(b) for the analysis of the remnants in the northern portion of the basin (Amazon biome), we used an adjusted grid with 965 hexagons, which corresponds to 81% of the TRB area;

(c) To analyze the remnants in the southern portion of the basin (Cerrado biome), we used an adjusted grid with 290 hexagons, corresponding to 19% of the TRB area.

This way, it was possible to analyze the geospatial changes from 1985 to 2018 in all remaining forests and savannas in the 03 core areas defined in the study objectives. Therefore, these hexagons were our analytical units and served to summarize the spatio-temporal dynamics of the remnants of the NVC in the entire basin area, in the Amazon biome area, and in the Cerrado biome area comprised of the Tapajos River basin (for more details on the hexagon grid, see Figure 2d).

Once the TRB database of all raster and vector files was consolidated in ArcGIS Pro - version 2.6, the data were exported to Grass-GIS - version 7.2.2, where the landscape metrics ran together with the LS- METRICS package - version 1.0. The basic procedures performed with this two software and the hexagon method used in the spatial analysis of the remnants are detailed in the articles (Ribeiro et al., 2009; Amaral et al., 2019). In addition, the details of computational operations and scripts generated in Python for Grass-GIS and LS-Metrics programs are explained in the works of Niebuhr (2018), Niebuhr et al. (2020), and Tonetti et al. (2022) and publicly available at the link: <https://github.com/LEEClab/LS_METRICS>.

Newer versions of Grass-GIS, v.7.2.2, had incompatibilities with LS-Metrics algorithm base - v. 1.0, so we advised those interested in using up to version 7.2.2 of Grass-Gis. After carrying out the geoprocessing operations of geometric study of the remaining habitats of TRB in GRASS - GIS tool (7.2.2), the results of metrics were edited in a spreadsheet in .txt format for graphical editing of the results in the R package (v. 3.6.1), such as basin maps, histograms, chart plotters, and regressions. More details of computational operations and Python scripts used in the study of landscape metrics in Grass-Gis environments are in the following articles (Neteler et al., 2012; Wegmann et al., 2018).

2.7 Landscape metrics and the analytical unit used

A set of six landscape metrics was used in the calculations of all NVC remnants in Tapajos river basin, following the analytical criteria of 03 core areas defined in the study. Here, NVC is the classification that aggregates all the remaining Forests and Savannas analyzed in the basin from 1985 to 2018. The metrics used were: (1) Number of Fragments – NP; (2) Size of Fragments – PS (hectares); (3) Fragment Edge Percentage – ED (%; we considered pixel resolution limit of plus or minus 30 meters); (4) Fragment Isolation – IS (external distance in meters from the edge to the nearest neighbor); (5) Fragment Interiority – IN (negative internal distance in meters from the edge to the center of the fragment); (6) Percentage of Remnants – RE (%; all lost patches of forest and savannah together).

All metrics used in this study were traditional metrics already established in the Landscape Ecology literature, based on the articles by McGarigal and Cushman (2002) and Botequilha-Leitão et al. (2006), except for the metric "Interiority" proposed by Niebuhr (2018). This metric measured the interiority of the fragment and was created to explain the loss of area and the isolation of small and irregular forest remnants in the studies developed by the author in Central Amazon and Atlantic Forest. Although it has not been applied in another study to explain the reduction and insularity of these fragments in the agricultural matrix, we will use it to show the geometric differences studied in TRB forest and savanna fragments.

Interiority is based on the internal Euclidean distance taken from the center of the fragments to the edge of the fragments, multiplied by -1, to differentiate from isolation distance, which is the external distance from the edge of the fragments to the outer edge of the nearest neighbor, which is a positive measure. Thus, the more negative the values found; the greater our fragments' interior area would be in the landscape within the hexagons. Therefore, this is best for the analyzed landscape as there would be a more negligible edge effect between the considered fragments.

The interiority metric also considers the fragments' general shape and uses the edge pixels' measurement to calculate the distance to the center of the fragment. Thus, the more elongated the fragments, the smaller the (negative) distances found and the less diversity because it intensifies the edge effect in landscape remnants (Laurance et al., 2002; Peres et al., 2010; Pfeifer et al., 2017). On the other hand, metrics of area or percentage of edges do not consider the attribute of the shape of the fragments and therefore were less elucidative (Niebuhr, 2018).

In this way, we calculate the area, the functional connectivity, the isolation of the fragments in the matrix, and the site relative to the fragment size. The functional connectivity is the sum of all functionally related areas (given the dispersion capacity between the fragments clearings in vegetation for a hypothetical group of fauna), and isolation is the measured distance between these fragments in the matrix (Martensen et al., 2008 and Ribeiro et al., 2009).

To avoid sampling error, the hexagons located on the edges of the perimeters of the entire basin and the boundaries of the North and South portions of the basin, we considered for calculation purposes only the parts of the hexagons within the analyzed region, with remainders of all hexagons located beyond the cut edges.

In addition, we also classified our base maps into edges and interiors for each type of remaining habitat analyzed. In this way, all remaining vegetation pixels were classified as edge and interior within the entire TRB area; edge and interior of forest and savanna fragments in the northern Amazonian portion of the basin, and edge and interior of forest and savanna fragments in the southern part of the Cerrado biome within the basin. In each of these subdivisions, we used an edge width of 60 meters, which means that depths smaller than 60 meters were classified as fragment edge, and values greater than 60 meters were classified as fragment interior. Thus, the edge and interior cover for each hexagon was calculated for all remaining forest and savanna fragments in 03 Core-Areas defined in the TRB fragmentation study.

Similarly, we measured the interiority of all remaining forest and savanna habitats in the basin's NVC, i.e., we measured the interiors of all forest and savanna patches in 03 analyzed Core-Areas within the basin. We calculated the Euclidean distance (meters) from each pixel in the fragment to the edge of the nearest neighboring fragment. For convenience, we used a negative sign for the found values of habitat interiority so that smaller negative values mean that the farther a pixel is within the habitat, considering the reference edges of the nearest neighboring habitat.

And finally, to calculate the habitat isolation metric, we also measured the Euclidean distance (meters) from each pixel within the anthropogenic matrix to the edge of the nearest habitat. In this case, we used the positive sign to represent values found so that the higher positive values mean the further a pixel is within the anthropogenic matrix, considering the edges of the neighboring reference habitat. This gave us an idea of the isolation of the remaining habitats within the agricultural matrix.

2.8 Assessment of accuracy and scales of raster maps

We produced two types of information in this study: cartographic, with maps showing the evolution of fragmentation within the TRB in the hexagon grid, and graphic, with histograms, chart plotters, and regressions that summarized the results of the six metrics used here. All maps generated in this study are presented at the same cartographic scale and were prepared from rasters of land use made available by MapBiomas for the basin. In addition, the data downloaded from the basin were standardized at levels 1 and 2 available at 1:1000,000, significantly reducing problems related to the accuracy of cartographic data and scales worked. Thus, the LULCC and NVC fragmentation results summarized in the maps from 1985 to 2018 were acceptable, considering the scale of 1:1000,000 worked and the limitations inherent to the spatial resolution of the LANDSAT series (TM5 and ETM+7 sensors), with pixel 30 meters on the ground.

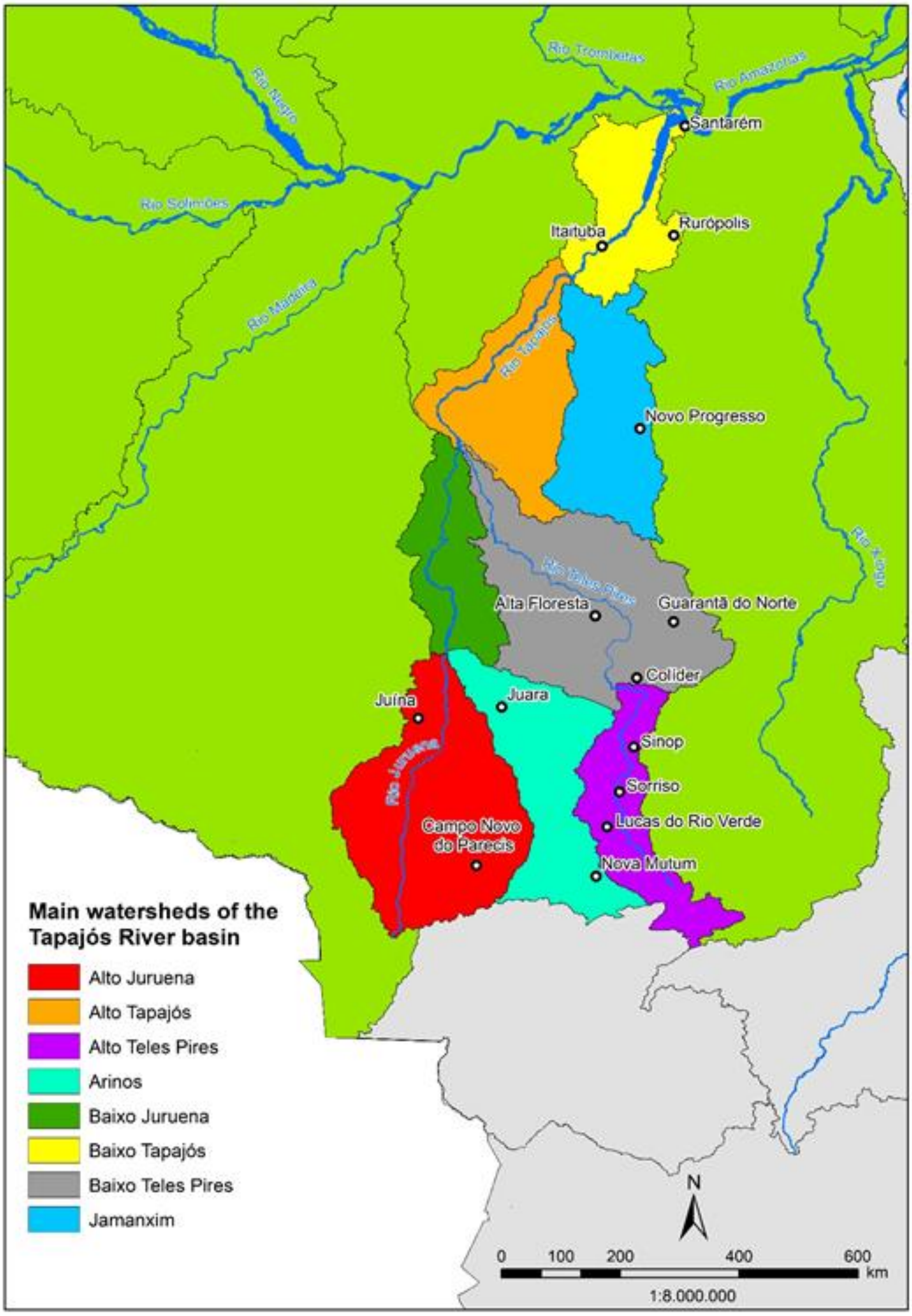
2.9 Statistical analysis of the fragmentation events

Below we presented the description of the methods used in the multivariate analyses. Two hypotheses about the fragmentation of TBR were considered, considering the time of occurrence of events in the North and South portions of the basin and the frequency of events between 1985 - 2018. For that, we used multivariate analysis techniques: Principal Component Analysis (PCA). This method was essential to identify which metrics studied the most correlated between the principal independent components and the forest and savanna remnants analyzed in the Amazon and TBR Cerrado. Cluster Analysis (CLUSTER) was necessary for classifying groups from different periods of fragmentation in the basin so that events within the same Clusters present the most remarkable similarity between the metrics used and the years sampled, according to the criteria given by Anderberg (1973) and Jolliffe (2002).

We used the PCA to obtain the main dimensions (principal components) so that the information could represent the most significant possible variance of the analyzed data set (Ringnér, 2008; Bro & Smilde, 2014). The purpose of Cluster analysis was to arrange objects that had similarities within the same group and dissimilarity between the analyzed groups, considering the Agglomerative (hierarchical) and Kmeans (non-hierarchical) clustering methods (Anderberg, 1973; Cushman & Mcgarigal, 2019).

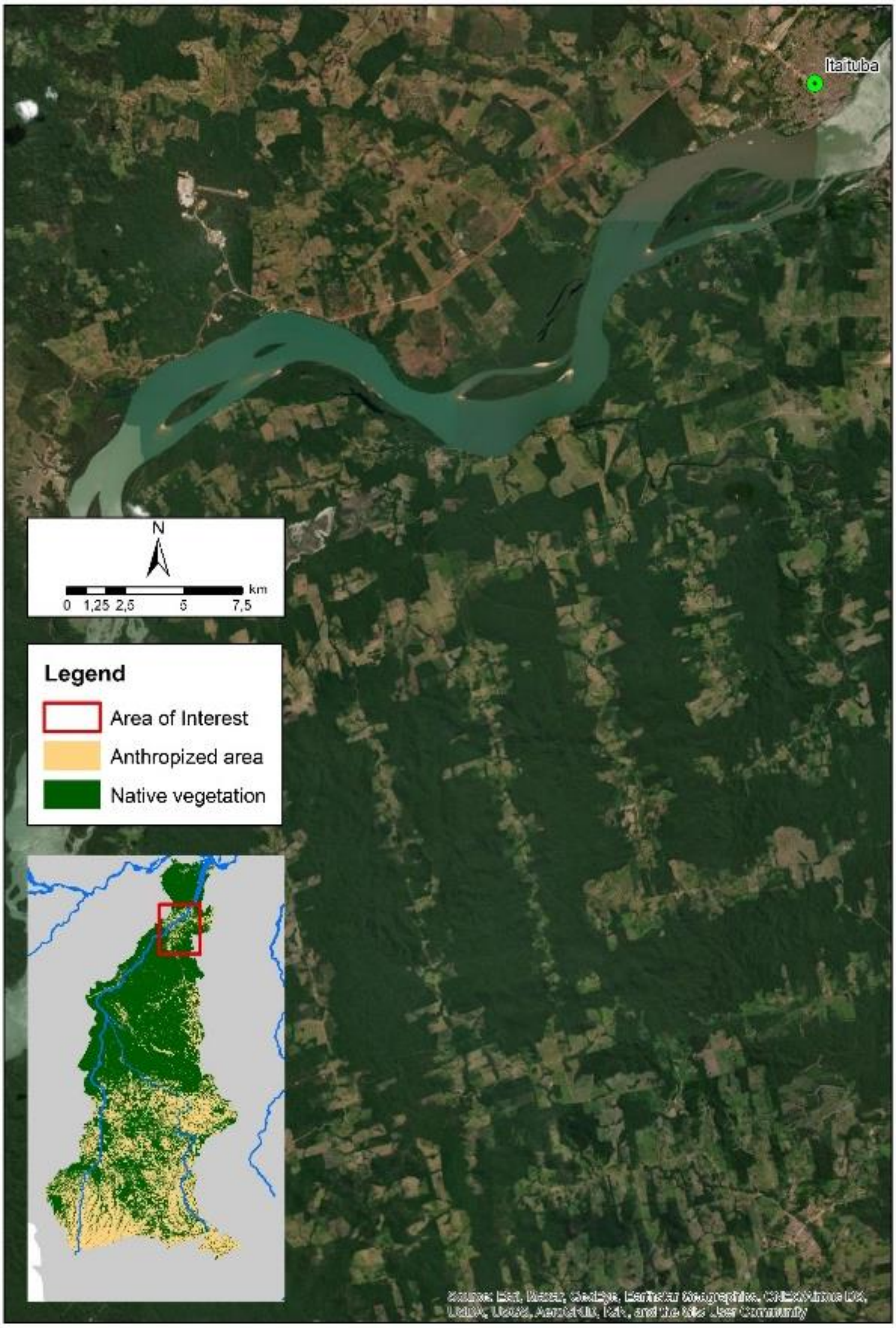
The analyzes mentioned above were performed in R software, version 3.6.1, through the prcomp(), hclust(), and kmeans() functions, for PCA technique, Agglomerative clustering, and Kmeans clustering, respectively. The routines used in R followed the criteria shown by Kassambara (2017).

Figure 2 (a) - Tapajos river basin characterization: Delimitation of the dynamic contribution area of the Tapajos River basin with its main hydrographic sub-basins (IBGE, 2022 and IGISMAP, 2022).



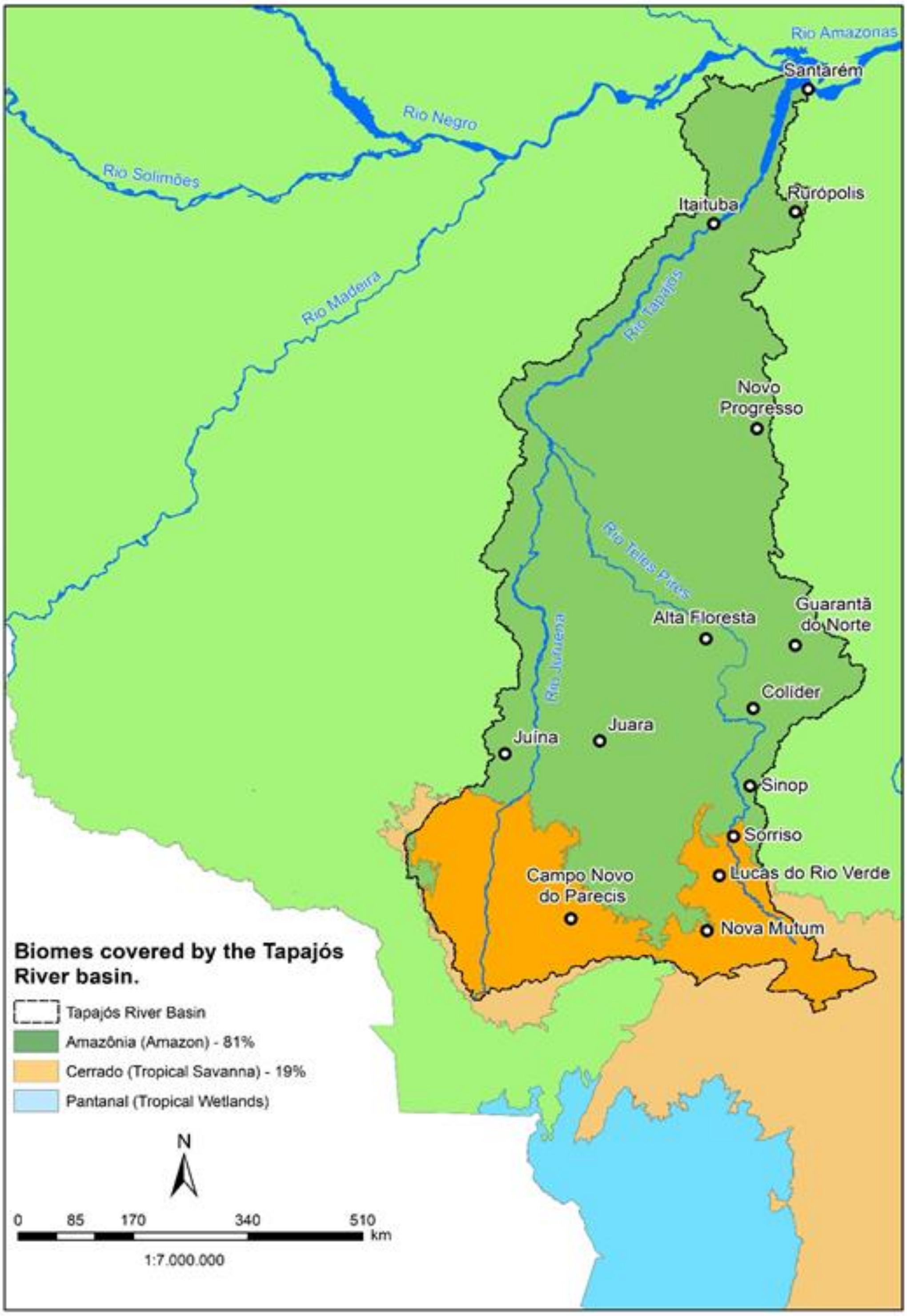
Source: MapBiomas (2021).

Figure 2 (b) - Clipping – Settlement model of rural properties carried out by INCRA in the Amazon. (Source: Compiled BaseMap ESRI and MapBiomas, 6th Collection 2021).



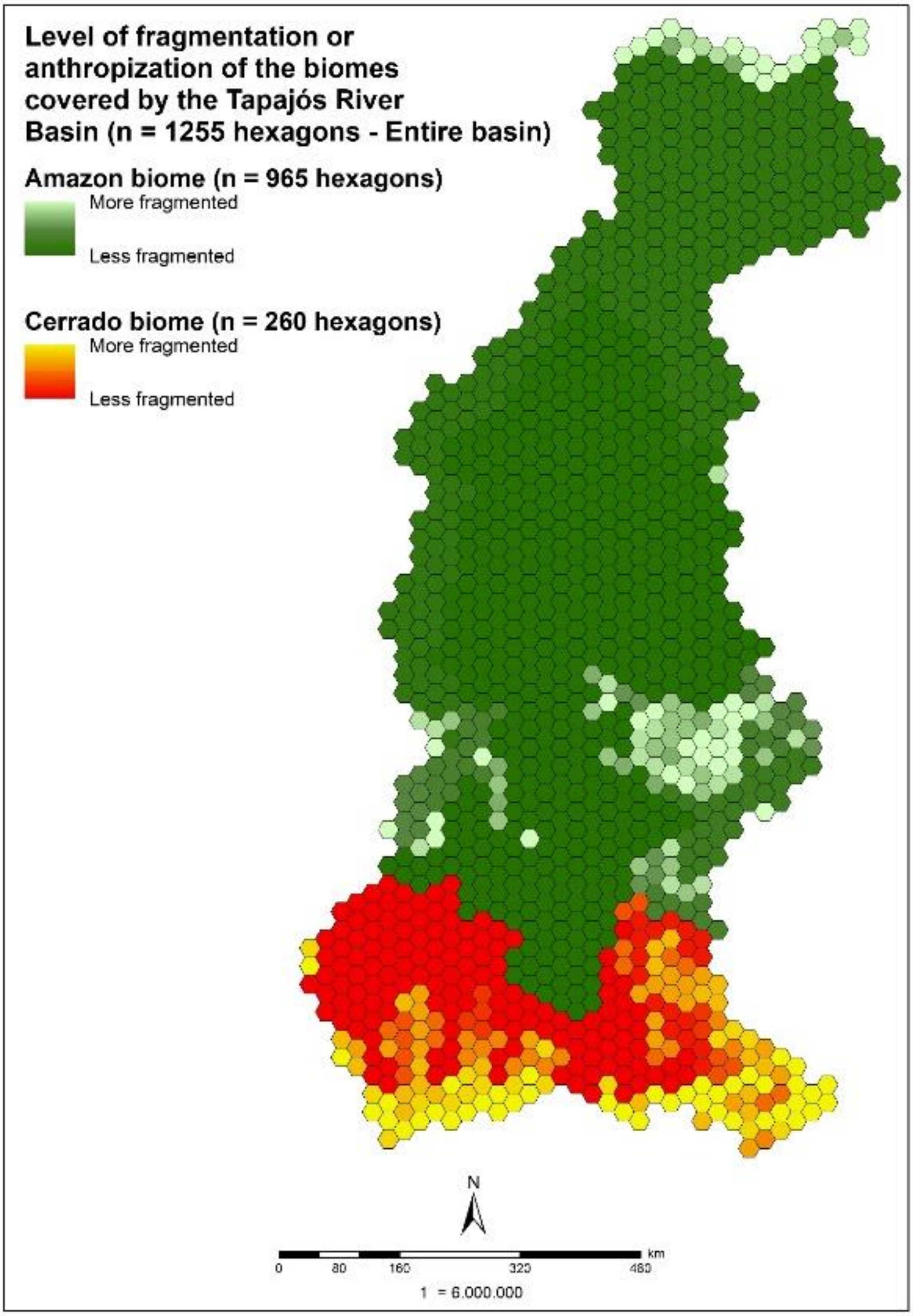
Source: MapBiomas (2021).

Figure 2 (c) - Tapajos River Basin, showing the physical delimitation of Cerrado (19% - Southern Portion) and Amazon (81% - Northern Portion) biomes within the basin (IBGE, 2022 and IGISMAP, 2022).



Source: Authors.

Figure 2 (d) - Grid of analytical hexagons in Core-South Area (Cerrado Biome) and Core-North Area (Amazon Biome) within the entire TRB área.



Source: Authors.

3. Results and Discussion

Due to the large number of analyses performed, we obtained many results to explain the fragmentation in three Core-Areas defined within the TRB in the thirty-three years of the study. In this way, we presented and then discussed each of them to facilitate the reading and understanding of the reader.

We ran a total of six metrics that resulted in 82 analyses of the geospatial study of the basin's remaining forest (Fo) and savanna (Sa) habitats. We presented these in maps, histograms, chart plotters, and regressions that explain the fragmentation occurring in the basin in the last 40 years.

Analyzes of six landscape metrics and hypotheses raised about the fragmentation of the basin between 1985 and 2018 are summarized below. We selected those results that best characterized the patio-temporal dynamics of the NVC remnants. Tables 1 and 2 showed the average results of the six landscape metrics of the Forest and Savanna fragments in the North (Amazon) and South (Cerrado) portions in the studied period.

Table 1 - Synopsis of the results with the averages of the six landscape metrics analyzed in the eight scenarios (1985-2018), by NVC typology in the Amazon Biome.

Period	**Number Patches (NP)**		**Patches Size (PS, ha)**		**Edge of Fragments (ED %)**		**Interior of Fragments (IN, meters)**		**Fragments Isolation (IS, meters)**		**Remnents (RE %)**	
	Forest	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**
1985	31,71	37,84	44.630.291,72	88,00	1,68	0,24	-3.503,13	-33,22	1.746,19	11.075,32	93,65	0,46
1990	40,11	53,14	43.418.197,80	104,42	2,09	0,35	-2.638,46	-33,59	1.371,99	9.777,39	91,59	0,66
1995	57,13	45,35	20.212.832,25	124,97	2,36	0,31	-2.628,78	-35,66	1.101,21	11.557,63	88,85	0,59
2000	69,41	55,04	17.862.959,70	79,81	2,80	0,33	-2.581,39	-34,46	1.379,05	11.691,99	84,20	0,63
2005	88,73	57,74	15.077.685,48	95,84	3,17	0,38	-2.152,67	-36,07	1.078,24	11.657,37	78,77	0,78
2010	94,17	47,46	14.811.909,58	58,21	3,36	0,25	-1.716,16	-33,20	748,20	12.817,07	77,02	0,46
2015	103,43	53,86	13.765.148,11	54,34	3,48	0,30	-1.721,47	-31,92	162,53	9.551,55	75,71	0,51
2018	115,86	66,29	13.658.865,53	57,97	3,69	0,31	-1.868,11	-32,47	999,74	9.954,52	74,91	0,53

Source: Authors.

Table 2 - Synopsis of the results with the averages of the six landscape metrics analyzed in the eight scenarios (1985-2018), by NVC typology in the Cerrado Biome.

Period	**Number Patches (NP)**		**Patches Size (PS, ha)**		**Edge of Fragments (ED %)**		**Interior of Fragments (IN, meters)**		**Fragments Isolation (IS, meters)**		**Remnents (RE %)**	
	Forest	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**
1985	169,29	218,56	28.874.708,00	535.663,16	4,38	6,39	-476,72	-212,82	705,03	511,73	42,47	43,31
1990	156,41	212,57	27.598.927,39	434.602,75	4,22	5,92	-431,19	-229,64	755,26	505,71	40,86	42,12
1995	160,72	253,52	13.067.510,91	295.770,97	4,26	6,22	-416,76	-232,24	761,08	512,12	39,79	38,33
2000	152,42	254,43	11.070.798,74	318.483,93	4,22	5,64	-362,80	-255,18	778,99	518,35	37,58	35,98
2005	150,65	278,69	7.502.603,73	188.725,49	4,28	5,49	-306,29	-234,27	743,71	507,99	33,99	32,05
2010	153,86	277,64	7.558.764,49	191.245,23	4,23	5,27	-306,70	-222,01	729,21	532,68	33,69	31,11
2015	154,69	287,69	7.676.322,98	189.901,20	4,35	5,20	-263,36	-215,93	661,11	515,41	33,62	30,05
2018	186,96	342,00	7.724.164,30	188.520,09	4,67	5,60	-266,57	-223,73	672,83	494,62	33,19	30,06

Source: Authors.

It is important to emphasize that interiority was one of the six metrics used to measure fragmentation in this study, first applied to explain the reduction and isolation of habitats in the NVC across the TRB area following the survey Niebuhr (2018). Since then, this metric was no longer used to explain the shape or insularity of vegetation remnants. However, this study proved to be more robust and explanatory than the connectivity of remnants metric. We used the connectivity metric (60 and 120 meters) in the first analysis of the work, but it was not used anymore because it could not explain the isolation of the basin fragments. More information about the "Interiority" metric can be obtained from the following link – https://github.com/LEEClab/LS_METRICS/wiki/EdgeH.

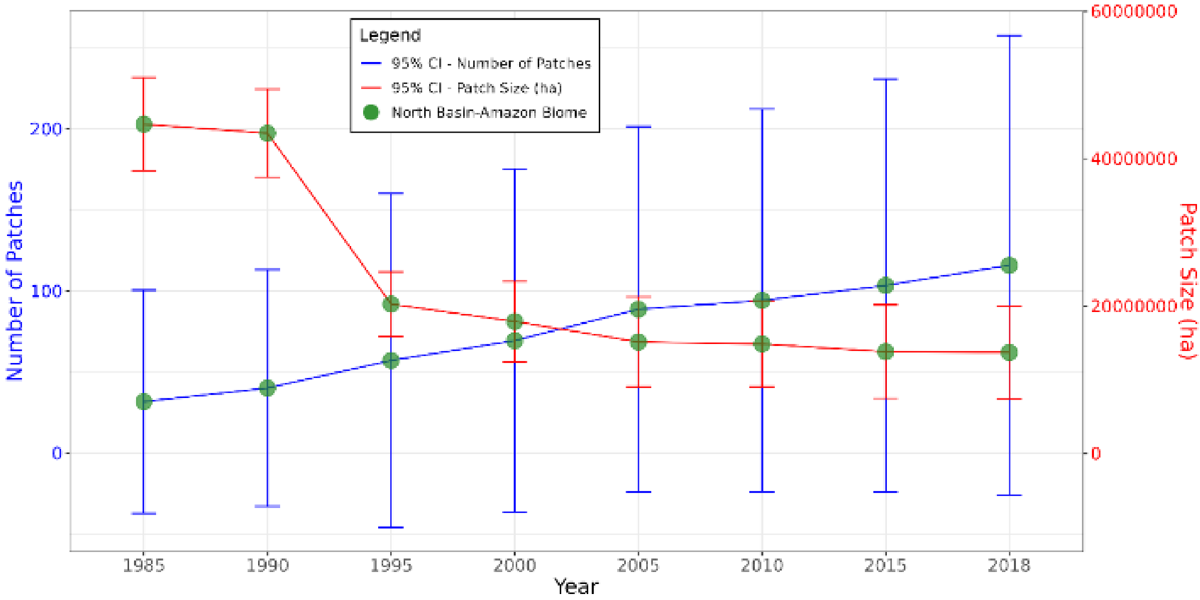
3.1 Metric – Number of fragments (NP) vs. Size of fragments (PS) in the entire TRB area

Figures 6 and 7 showed the relationship between the number of remnants (NP) versus the size of these remnants (PS). From the crossing of these two metrics, we analyzed the whole remnants of the NVC (Fo+Sa) measured in the North and South portions of the basin. For calculation purposes, the number of hexagons was (n) = 965 and 290 in the North and South portions of the basin, respectively.

Figure 3a below showed in the northern portion of the basin (Amazon biome) the increase in the number of all remaining NVC with consequent loss of areas of the fragments over the analyzed period. The result obtained for the standard deviation of the number of fragments was higher than the standard deviation obtained between the sizes of the analyzed fragments. In 1985, the number did not exceed 50 total fragments in the northern portion of the basin. Many had huge areas ranging from 40 to 60 million hectares (ha). These remnants comprised a continuous landscape of ombrophilous forests dominating extensive areas within the northern portion of TRB. Twenty years later, in 2005, the number jumped to more than 100 fragments in the landscape, and their areas were reduced to half their original sizes. However, many still had significant regions with 20 million ha. In 2018, the number of total remnants doubled again in the northern landscape of the basin, rising to more than 200 fragments, and their areas reduced to fragments between 5 and 10 million hectares.

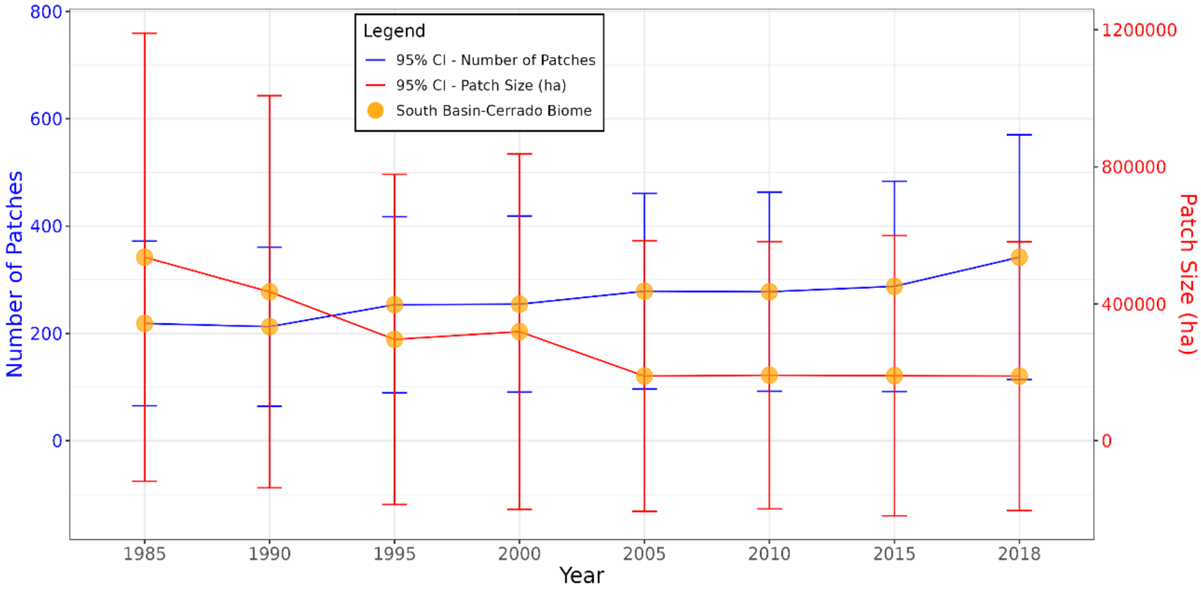
The relationship between the Number of Total Fragments (NP) versus the Size of Fragments (PS) was analyzed in the remnants of Forests and Savannas in the:

Figure 3 (a) - Northern portion (Amazon biome) of the Tapajos River basin in the period from 1985 to 2018. Green dots represent the average variation of NP and PS in the Amazon biome, and the blue and red vertical lines represent standard deviations of NP and PS.



Source: Authors.

Figure 3 (b) - Southern portion (Cerrado biome) of the Tapajos River basin from 1985 to 2018. Orange dots represent the average variation of NP and PS in the Cerrado biome, and the blue and red vertical lines represent the standard deviations of NP and PS.



Source: Authors.

Figure 3b above shows the increase in the number of fragments in the southern portion of the basin (Cerrado biome) among the whole remnants of the NVC (Fo+Sa) and the consequent reduction in these remnants in the period from 1985 to 2018. The curves showed fragmentation dynamics slightly more accentuated than that observed in the Amazonian portion of the basin, with higher numbers and smaller areas between the analyzed forest and savanna fragments. In 1985, we measured a number between 50 and 400 patches, while areas varied widely, with patch sizes between 1 and 1.2 million ha. In 2005, twenty years later, the number jumped to 100 and 500 fragments in the landscape and its reduced areas, with the most significant fragments below 600 thousand ha. In 2018, the number increased again, reaching more than 600 fragments in the landscape, with areas even smaller than 500 thousand ha in the southern portion of the basin. We can observe for all these years that the standard deviation of the regions in savanna and forest fragments of the south part of the basin (Cerrado biome) was more significant than the standard deviation of the areas of these fragments measured in the Amazon portion of the basin. This finding becomes more evident when we compare Tables 1 and 2 the data on the number of fragments (NP) and area of fragments (PS) of forest and savanna analyzed between 1985 and 2018 in the Amazon and Cerrado biomes on TRB. The variation observed in the Cerrado biome between the two variables – NP and PS was more pronounced than in the Amazon biome.

In general, analyzing the two compartments North and South of the basin, we observed that, every 20 years, the number of total fragments in the landscape doubled while their areas were reduced by half. This more significant variability found for the values of standard deviations in the regions of Cerrado remnants most likely characterizes a slightly greater fragmentation, possibly since the occupation took place in the southern portion before the Amazon portion of the basin. Indeed, data presented by Domingues & Bermann (2012) and Carneiro & Costa (2016) on land management and use in Brazilian Cerrado confirmed the hypothesis that the southern portion of TBR was first occupied, in the early 1970s, explaining the greater number of smaller fragments found in the southern portion of the basin. In the south part of the basin, although the results are more subtle than the number and areas of remnants of the northern portion of the basin, this is partly since most of the fragments in 2018 in the southern part of the basin were still large and with more 2 and 3 million ha, this made the temporal analysis of Amazon biome fragments within the TRB are complex (Laurance et al., 2018; Montibeller et al., 2020).

The isolated analysis of the number of fragments (NP) explained very little about fragmentation. It only shows an increase in the number of fragments in the matrix over time. However, when we analyzed and cross-referenced the number of fragments (NP) with the size of these fragments (PS) from a known area, the information collected was much more robust about the fragmentation of the landscape (Cushman & Mcgarigal, 2008). In this analysis suggested by the authors, it is observed in Figures 7 and 8 that there was an increase in the number of landscape fragments, and the curve formed tends to an exponential function – $f(x) = a^x$, while the loss of area of the fragments described a curve that tends to logarithmic function – $f(x) = \log a^x$. That is, the relationships observed between both functions were inverse, and the more we advance with the fragmentation in time, the more we lose in the availability of matrix habitats.

The studies have confirmed this inverse relationship and showed that the reduction of the remaining habitats of modified landscapes directly interfered with the survival of populations of resident fauna (Bailey et al., 2010; Fahrig, 2013). Although landscape ecology is a relatively new science, the studies conducted by Helliwell (1976) and Forman & Godron (1981) more than forty years ago already described these patterns found in the spatial configuration of the remaining habitats of intensively modified areas.

Other variables related to fragmentation, such as edge effect, functional connectivity, and isolation of fragments, were directly dependent variables on the number and area of these fragments in the agricultural matrix (Forero-Medina & Vieira, 2007; Hagen et al., 2012; Vieira et al., 2018; Hansen et al., 2020). Studies of this magnitude are increasingly crucial in tropical forest and savanna environments to know the breaking point of ecosystems. The studies clarify what is the final spatial conformation of the fragments and how much of the original NVC we must preserve not to collapse the life cycle of the local biotas (Peres, 2001; Santos et al., 2008; Ripple et al., 2015).

3.2 Metric – Size of fragments (PS) of forests and savannas analyzed in the north and south portions of the basin

Figures 4a and 4b of the following regressions show the evolution of fragmentation and explain the loss of areas between the remaining forest and savanna habitats within the North and South portions of TBR from 1985 to 2018.

Analysis of Figure 4a above shows the area loss of remaining forest fragments in the northern portion of the basin (1985-2018), where fragmentation was more significant in the period from 1985 to 2000. From 2005 onwards, the second period in which fragmentation advanced more slowly in the landscape and resulted in less area loss of the remaining forests, when the percentage of NVC was below 75 and 50%, with areas ranging from <100 to 100 thousand hectares. Considering the 33 years of the study, the loss of forest habitats occurred in all analyzed scenarios, but the presence of large fragments more prominent than 10 million ha remained high in the northern portion of the basin until the end of 2018.

Figure 4b below shows the evolution of fragmentation and area loss of savanna fragments in the southern portion of the basin (1985-2018). The area reduction in the analyzed savanna fragments was more remarkable than the forest fragments in the northern part of the basin - the Amazon biome, showing evidence of intense deforestation and older in the southern portion of the TRB. Although, when we compare the fragmentations in the northern and southern parts of the basin, the number of fragments (NP) was higher in the north portion of the basin (see Table 2), this is since the southern part represents less than 20% of the area of the basin. Analyzing the period from 2000 to 2018, in the southern portion of the basin, when the NVC was below 25, and 50% of its original area, the area of savanna fragments ranged from 100 to 10,000 ha.

Worldwide studies with fragmentation and area loss of forest remnants in tropical regions corroborate our results for reducing the size of remaining fragments of TRB. For example, Hansen et al. (2020) studied the continuous reduction of tropical forests distributed in African Congo, Southeast Asia, and Central Amazon. They showed a significant loss of forest remnants due to the indiscriminate land use in these regions.

Atlantic Forest biome, with 1.5 million km² distributed along the Brazilian coast, has currently less than 12% of its original coverage, where 80% of analyzed fragments are < 50 hectares and the average isolation between them reaches 1500 meters. Also, in the most compromised sites, isolation radius reaches 10 km or more among the remnants (Ribeiro et al., 2009 and 2011). Moreover, in 2015, the Amazon region had already accumulated deforestation in the last 40 years, equivalent to 762,979 km² or 185 million ha of the NVC; accessed on 08/10/2021: <https://agenciabrasil.ebc.com.br/geral/noticia/2014-10/amazonia-acumula-762-mil-km2-de-desmatamento-em-40-anos-diz -study>. If we added to these values deforestation that occurred from 2015 to 2020, we would reach more than 20% of the original Amazonian cover converted into pastures, crops, and other forms of land use. We draw attention to the fact that this territory has been modified to a great extent in the last 20 years, according to sources from the Amazon surveillance program – DETER/INPE; consultation carried out on 08/10/2021: http://www.inpe.br/faq/index.php?pai=6.

Reanalyzing Figures 4b and 4c in the period from 1985 to 1995, in the northern portion of the basin, there was a more discreet loss in areas of remaining forests, while in the southern part of the basin, in the same period, fragmentation was already practically consolidated in 1985. As a result, remnants showed areas ranging from < 100 to 10,000 hectares, comparatively much smaller than the areas of the remnants measured in the northern portion of TRB. On the other hand, analyzing the period from 2005 to 2018 in the southern and northern parts of the basin, it is observed that remaining forests and savannas lost areas again at the end of the period, characterizing a rewarming of fragmentation throughout the basin (see Table 2). Data on fragmentation with tropical forests show that at the beginning of the process, forest remnants were fewer, their areas were large, and they quickly lost areas with the advance of fragmentation in the agricultural matrix (Laurance et al., 2011; Hansen et al., 2020).

Niebuhr (2018) analyzed the area and isolation of forest fragments in Central Amazon and Atlantic Forest (SE Brazil). He found that most of the fragments in the most degraded areas of Amazon Forest have areas ≥ 50,000 ha, while in more fragmented areas of Atlantic Forest the largest measured fragments hardly exceeded 10 ha. Laurance et al. (2018) and Montibeller et al. (2020) found similar results when they analyzed even after 20 years of deforestation and intense fragmentation, Amazon Forest fragments, the remnants still had large areas with thousands of hectares and little isolated from each other. These differences vary between the geographic locations, biomes, flora, and taxa. The history of deforestation in Atlantic Forest goes back 500 years, while in TRB, it has been occurring in the last 40 years, although with much more efficient tools and technologies to cut the forest.

Other studies on area loss, isolation, and fragmentation patterns in the remaining habitats of the Atlantic Forest and Amazon Forest corroborate the results of the present study for the remnants of TRB. Many fragmented areas of Atlantic Forest presented a fragmentation pattern with many small fragments isolated from each other in a very diversified agricultural matrix (Fleury & Galetti et al., 2003; Trindade et al., 2008; Ribeiro et al., 2011; Joly et al., 2014; VIeira et al., 2018). In the Amazon region, we usually find a pattern with large fragments in smaller numbers in the landscape and dispersed in a matrix with livestock, farming, or logging (Numata & Cochrane, 2012; Souza Jr et al., 2013; Barber et al., 2014; Laurance et al., 2018; Luther et al., 2020). Knowledge of the current scenario and form of management adopted in Amazonian agroecosystems is both the key and the solution for the sustainability and future resilience of the remaining fragments of NVC in the transition of Cerrado – Amazon biomes (Van Noordwijk et al., 2004; Chazdon et al., 2009; Defries & Rosenzweig, 2010; Power, 2010; Lapola et al., 2014).

3.3 Metric – Edge percentage (ED%) in forest fragments and savannas analyzed in northern and southern portions of the basin

Figures 4c and 4d of the regressions below show an increased edge effect in all scenarios in the North and South portions of the basin, but it was more intense from 1985 to 2000, fell in 2005, and then slowly increased again until 2018. With the reduction of NVC, the edge effect increased in two portions of the basin, especially for the remaining savannas of the southern part.

Figure 4c above, between 1985 and 2000, when NVC was more than 75% intact, the edge effect was below 5% for most forest fragments, with a few oscillating between 5 and 15% in the northern portion of the basin. From 2005, cover dropped to 50 to 75%, and we observed an increase in the number of fragments in the landscape with 10 and 15% edge, and we can see that from 2005 to 2018, the edge effect advanced more slowly in the landscape, remaining below 15% edge.

Figure 4d shows the most accentuated fragmentation of the landscape in the southern portion of the basin, with two distinct periods. In a more intense and extended first period, from 1985 to 2005, while NVC was between 75 and 100% intact, in most savanna fragments, the edge effect was below 10%, with a few fragments oscillating between 10 and 20%. In the second shorter period, which lasted from 2005 to 2018, the edge effect advanced more slowly in the landscape, and when the cover was between 25 and 50%, the edge effect in savanna remnants increased to 10 and 20%.

Indeed, the results for the edge effect in North and South portions oscillated between 1985 and 2018 in TRB (Figures 4). Still, they were progressive and characterized different episodes for fragmentation dynamics, especially in remnants analyzed in the southern portion of the basin. Dros (2004), Verhulst et al. (2010), Carneiro & Costa (2016), and Picoli et al. (2018) also confirmed in their studies of Cerrado biome significant losses and fragmentation in savanna formations in southern Amazonia, converted into areas of crops and pastures in large territorial extensions in the watersheds of Tapajos, Xingu and Tocantins rivers. The open gaps in the forest left many isolated blocks in NVC, which caused an increase in the edge effect between the remnants of agricultural matrix (Fahrig, 2013).

Forman & Godron (1986) demonstrated that the conversion of large natural areas by other agricultural ecosystems, such as planted pastures or monocultures, produced in the landscape the formation of isolated fragments. Those isolated fragments immersed in a surrounding agricultural matrix, increased the edge effect in the resulting fragments. With the increasing isolation of fragments caused by land use, a forest border was formed between the remnants and the occupied area of the matrix. This interface called the "Edge Effect," brought negative ecological consequences to the resident biota as the edges and isolation between these fragments increased (Galetti et al., 2003; Fahrig, 2013).

The edge effect has been described as one of the most present threats to tropical forest remnants worldwide. However, identifying and measuring it in the matrix fragments with the tools we have available today is not an easy task (Ribeiro et al., 2009; Porensky & Young, 2013). Nevertheless, today we know that the edges of the forest surrounding large areas of anthropic matrix generally negatively affect the communities of mammals, amphibians, reptiles, and birds that transit between forest remnants and the matrix (Pfeifer et al., 2017).

Pfeifer et al. (2017) performed a global review of edge effects on vertebrate populations at 22 threatened forest sites on five continents. The authors correlated these effects with more than 1600 vertebrate species. They found that more than 85% of the analyzed species suffered some negative impact on the abundance of populations, as individuals were distributed from the edge to the center of the forest remnant. This has been proven in elongated and narrow fragments of Atlantic Forest and Amazon (Hansbauer et al., 2008; Ribeiro et al., 2009; Tabarelli et al., 2010; Benchimol & Peres, 2015). That is, species that travel closer to the forest edges with the matrix are more affected than species that live closer to the core of the remnants (Mendes et al., 2016; Pfeifer et al., 2017).

The history of habitat fragmentation in the Amazon landscape is relatively new, showing the edge effect on the structure and functionality of fragments (Malcolm, 1994; Nascimento & Laurance, 2006; Laurance & Vasconcelos, 2009). however, amazonian studies are more significant in the number of articles produced than publications in neotropical savannas (Teixido et al., 2020).

Lovejoy et al. (1986) and Laurance & Yensen (1991) showed that the edge effect in Amazonian Forest fragments is caused by physical and biotic changes that occur at the edges of the forest, with impact proportional to the distances between the edges of the remnants in the matrix, and according to Laurance et al. (2007) reduces species diversity at these sites.

Laurance & Vasconcelos (2009) and Ribeiro et al. (2011) demonstrated that the edge effect in Amazon and Atlantic Forest remnants was directly related to the size of the fragments, and the smaller the areas, the more remarkable the edge effect recorded. However, Laurance & Vasconcelos (2009) also found large forest fragments with a high percentage of edge in the Amazon, but the authors did not explain the reason for this occurrence.

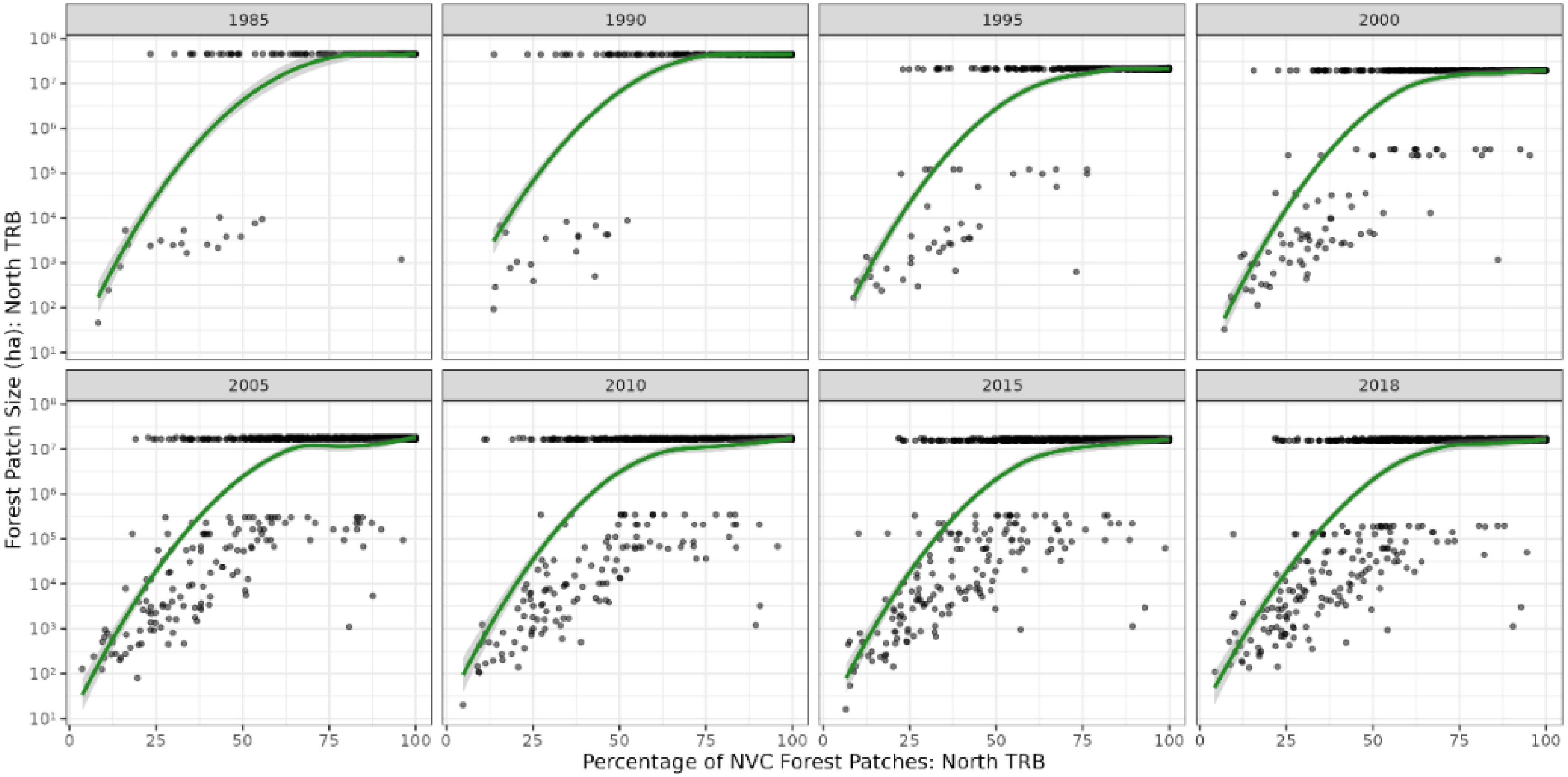
For Kapos et al. (1993), Murcia (1995), and Rodrigues & Nascimento (2006), the edge effect in tropical forests is more challenging to measure because the ecological interactions between the edge and the interior of the fragment are more dynamic than the processes observed in temperate forests. In Amazon, we still have the effect of the fall of large trees on the edges of the fragments, which cause gaps in the woods, increasing the edge effect in the remnants due to continuous deforestation.

Therefore, today it is still premature to compare the edge/area relationship in tropical forest fragments based on evidence of Ribeiro et al. (2011) when they studied the Atlantic Forest remnants and found a higher edge effect in small than in large forest fragments. On the other hand, in southern Amazonia, Laurance & Vasconcelos (2009) found high edge effects associated with both small and large forest fragments. This is a warning with these generalizations in the analysis of the edge/area relationship of Amazonian remnants because regional studies are starting in this vast territory, and more and more novelties are discovered every day (D'Albertas et al., 2018).

Through the joint analysis of the edges of remnants in Figure 4 and the areas of the remnants in Tables 1 and 2 showed in 2018 the following border/area relationships: North – Amazon portion of the basin, when the forest fragments presented the leading edge of 15%, their areas ranged from 10 to 10 million hectares; while in southern portion – Cerrado, when the savanna fragments had a top border of 20%, their sizes ranged from 1 to 1 million hectares. This evidence between edges/areas showed that there was a non-linear correlation of these variables in the two studied portions of TRB leads us to question whether this is a generalized trend common to all sizes of remaining fragments of the Southern Amazon, as reported by Laurance & Vasconcelos (2009).

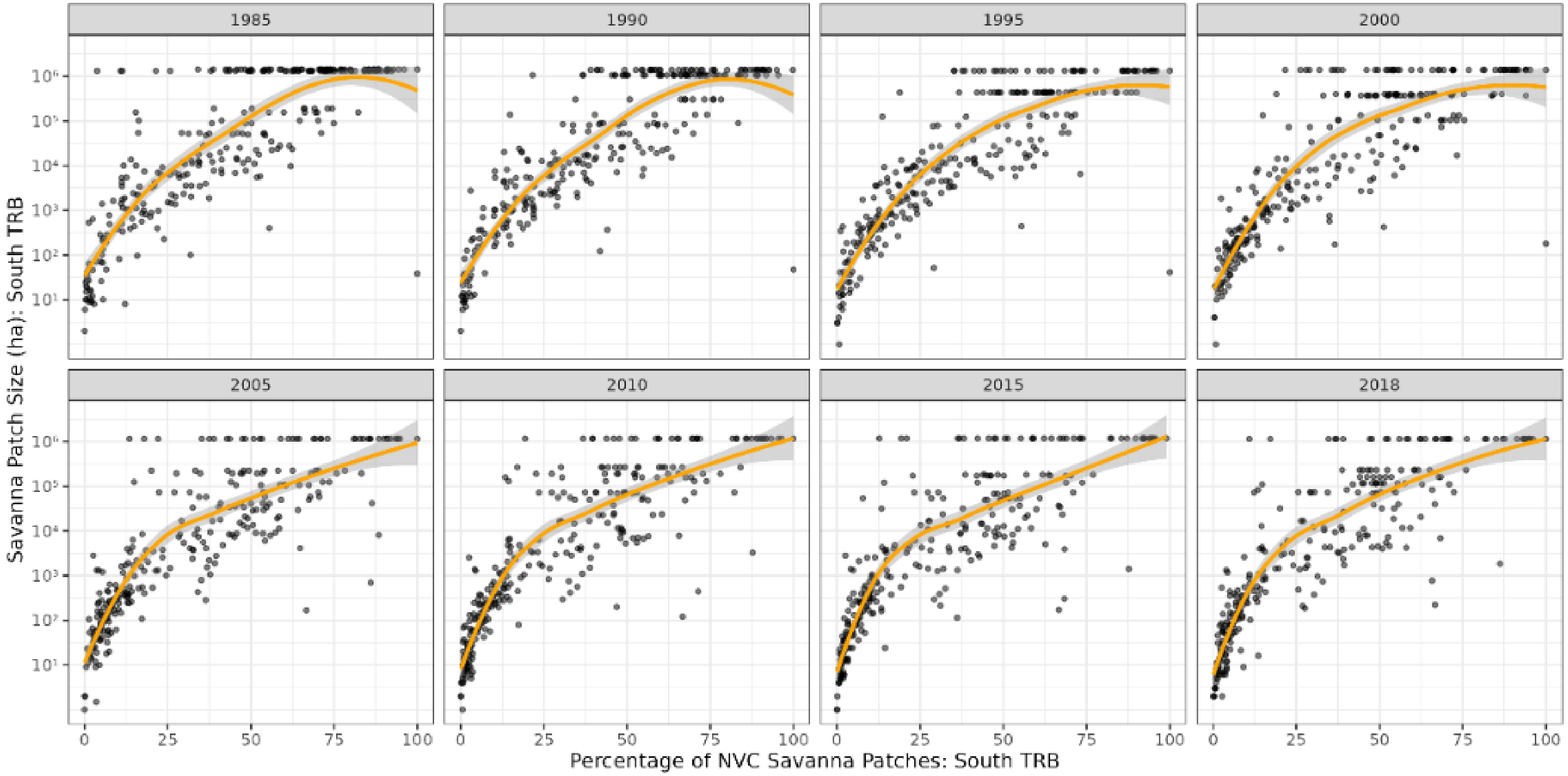
In this way, the edge effect in Amazon will be high and advance in the increasingly fragmented landscape, regardless of the floristics of the size of the fragment involved. With current knowledge about fragmentation dynamics and the role of forest edge areas in NVC remnants, we can state that the continued progression of fragmentation in degraded landscapes increases the effective edge area in all tropical forest remnants (Pfeifer et al., 2017; Fischer et al., 2021).

Figure 4 (a) - The regressions show on the X-axis the total percentage of the remaining NVC fragments an on Y-axis,: (a) the relative area of the Forest fragments within the Northern portion -Amazon biome.



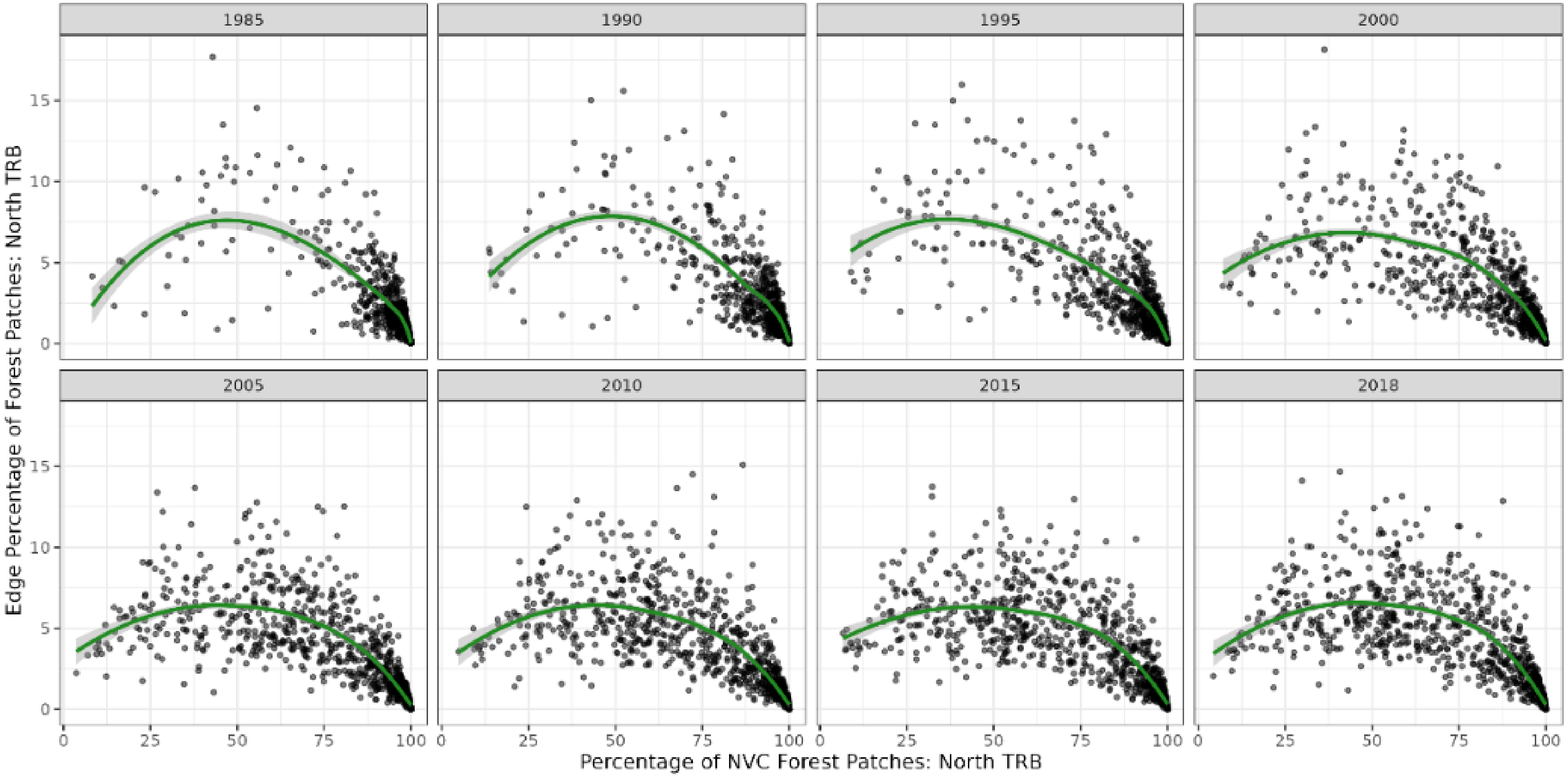
Source: Authors.

Figure 4 (b) - The area found only in the savanna's fragments within the southern portion - Cerrado biome.



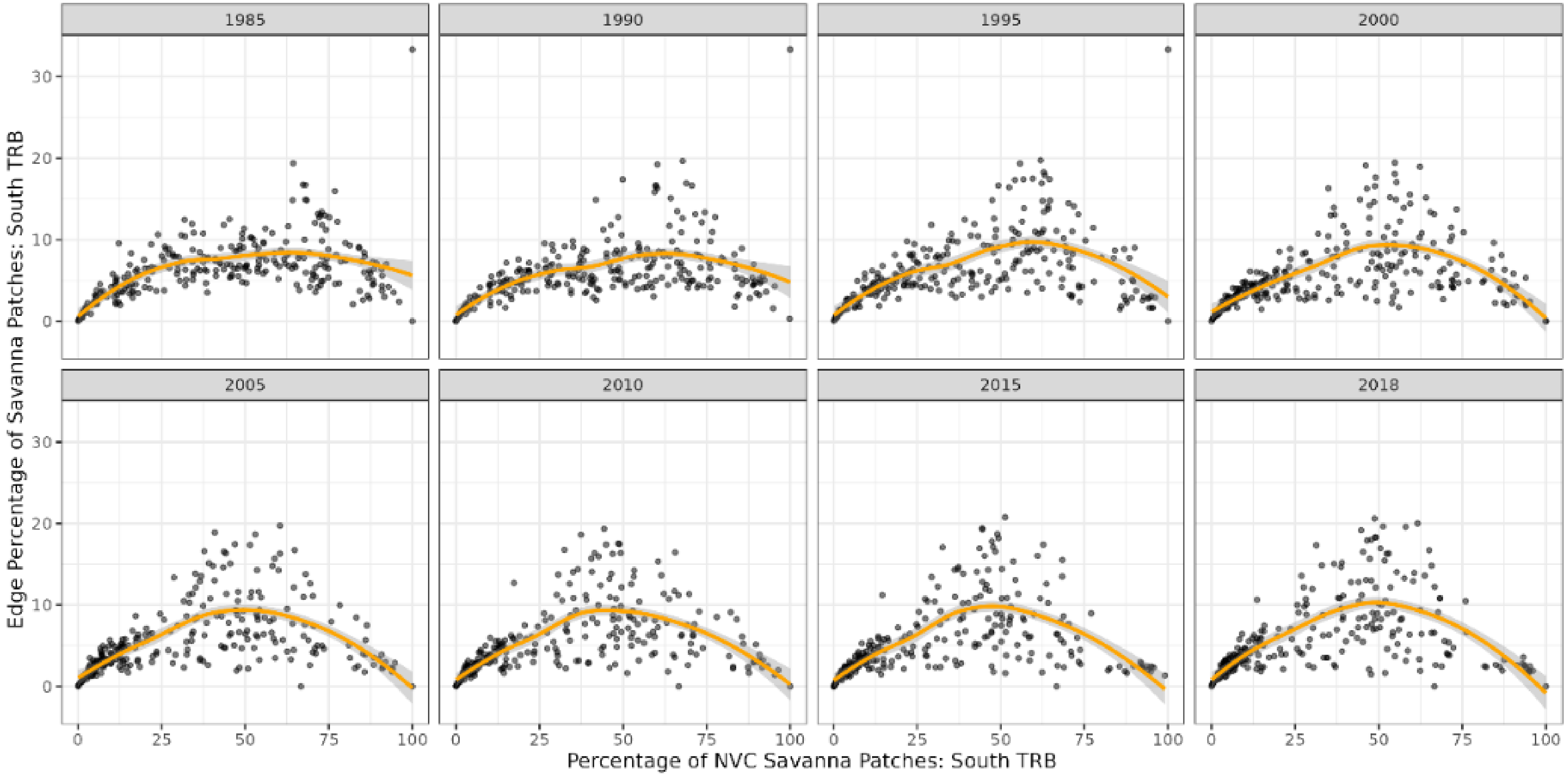
Source: Authors.

Figure 4 (c) - The percentage of edge only of forest fragments within the northern portion of the basin - Amazon biome.



Source: Authors.

Figure 4 (d) - the border percentage of only savanna fragments within the southern portion of the basin - Cerrado biome. Relative to the period 1985 to 2018.



Source: Authors..

3.4 Metric – Isolation distance (IS) of forest and savanna fragments analyzed in north and south portions of the basin

In Figure 5a below, the histograms show the isolation of forest fragments from 1985 to 2018 in the northern portion of the basin (Amazon biome). We can see a progressive increase among the three classes of isolation distances considered in the analysis. In 1985, 72% of the forest remnants were isolated at a maximum between 10 and 100 meters. In 2005, twenty years later, it dropped to 44%, and in 2018 it reduced again to around 42% of the remnants. The second insulation class from 100 to 1000 meters, which was approximately 20% in 1985, 20 years later, in 2005 it rose to 51%, and in 2018 it had slight variation, going to 53% of forest remnants. Finally, in the third-largest class of 1000 to 10,000 meters of isolation, the smallest variation in the period was observed, from 7.5% in 1985 to 4.2% in 2018 in the forest remnants of the basin.

In the northern portion of the basin, two distinct periods of isolation of forest fragments can be observed. One period of isolation is more intense and longer, lasting 20 years from 1985 to 2005, and the other is milder and shorter, lasting 13 years from 2005 to 2018, characterized by a dynamic of slower fragmentation with slight variation between the isolation classes of the remnants in this hydrographic compartmentation (see Figure 5a).

Results in 2018 showed that more than 90% of forest fragments were distributed in the following isolation classes: about 40% in the 10 to 100 m class and more than 50% of them in the 100 to 1000 m class, showing that the isolation advanced faster in the landscape mainly in the first period from 1985 to 2005. Haddad et al. (2015) studied the isolation of vegetation remnants from several tropical forests in the African, Asian, and South American continents. They found isolation patterns between the analyzed patches like the results found in TBR. They found that more than 50% of medium and large forest fragments with 300 and 1500 hectares were isolated by distances ≤ 1 km and ≥ 10 km in the most degraded areas. The isolation patterns described by Haddad et al. (2015) for other tropical forests also seem to be repeated in Neotropical forests.

Similar forest isolation scenarios were described by Ribeiro et al. (2009) in the Atlantic Forest biome, Carvalho et al. (2009) in the Cerrado biome for seasonal forests, and Laurance et al. (2011) in the Amazon biome in "terra-firme" forests of Central Amazonia. In addition, the authors found patterns of isolation between large and medium-sized forest fragments very close to the practices discussed by Haddad et al. (2015) and the results of the present TRB survey. Stabile et al. (2020) and Rosa et al. (2021) showed how intensive land use and indiscriminate occupation impacted. NVC in areas surrounding Tapajos watershed. Today, the basin has more than 50% of its plateau area degraded and has been increasing rapidly towards the basin depression in the last 20 years.

In Figure 5b, in the southern portion of the basin, there was a slight variation from 1985 to 2018 in all three isolation classes for savanna fragments. In the first 20 years of the study (1985-2005), 10 to 100 meters class decreased from 18.4 to 12.1% and then increased again to 14.9% in 2018. The second class (100 to 1000 m) had a progressive increase from 68.4 to 78.9% between 1985 and 2005, and in the following thirteen years, from 2005 to 2018, it dropped to 75.4% at the end of the period. In the third insolation class, from 1000 to 10,000 m, the variation observed was minimal and did not exceed 2% in the two periods studied.

Thus, analyzing the eight scenarios in Figure 5b, we found minimal variation between all insolation classes in the study period in the basin's southern part. This indicates that there was a period of fragmentation before 1985 and can be seen by comparing the differences between the three isolation classes of forest and savanna remnants in the two analyzed portions of TRB. Most likely, the fragmentation process would have started in a period before one studied, in this compartmentalization of the basin, so that the isolation of most of the fragments in the south of the basin was already consolidated in 1990, justifying the lower variability found between the classes of isolation. In fact, studies by Pivello (2011) and Carneiro & Costa (2016) showed the losses of savannas in the tributaries of the upper Tapajos and Xingu rivers, corroborating the hypothesis of occupation in a previous period in the southern portion of the Tapajos River basin.

The authors mapped the occupation showing that the increasing isolation of remnants of Cerrado biome occurred before the Amazon. However, studies with small remnants of savannas have shown the importance of this mesh of micro-habitats in the matrix as stepping-stones for the dispersion of small mammals in Cerrado – Amazon ecotone (Carvalho et al., 2009; Santos-Filho et al., 2012; Paula-Gomes et al., 2015).

However, this lower variability between the isolation classes of savannas in the southern portion is not fully clarified. Still, three vital pieces of evidence must be considered: reduction in deforestation rates between the 1980s and 2000s, natural regeneration of the remnants of NVC, or both possibilities interacting over time in the southern portion of the basin, as demonstrated in the articles – by Klink & Machado (2005), Davidson et al. (2012) and Chazdon & Guariguata (2016). Furthermore, the long-term study performed by Laurance et al. (2018) with habitat isolation proved that this evidence is present among all types of Amazonian NVC remnants.

With the current database on the consequences of insularization and loss of forest habitats in many threatened regions of the Amazon, there was no difference from what occurs in other tropical forests, such as African forests in Kenya (Brooks et al., 1999) and Ghana (Hill & Curran, 2003); Malaysia's forests (Hill et al., 2011); seasonal forests of Brazilian Cerrado (Santos-Filho et al., 2012 and Muylaert et al., 2016); Brazilian Atlantic Forest (Botequilha & Metzger, 2011 and Canale et al., 2012). The consequences of the growing number of open gaps are known on the edges of Amazon Forest, favoring the increase of recurrent fires, accelerating the isolation and reduction of forest remnants, and the rarity of species or even extinction of species of fauna that circulate between the edges of these isolated fragments (Michalski et al., 2008 and Benchimol & Peres, 2015).

3.5 Metric – Interiority of the fragments (IN) of forests and savannas analyzed in north and south portions of the basin

Figure 5c deals with the interiority of forest fragments about the total percentage of these remnants in the northern portion of the basin. In 1985 when the grid of hexagons indicated that 75 and 100% of NVC was intact, the forest fragments presented interiority ranging from 100 to 10,000 meters. Over the period, interiorization increased until 2000, showing that more fragments with interior distances smaller than 100 meters were subjected to more significant edge effects. Subsequently, in the second period, from 2005 to 2018, the interiorization of fragments remained more stable, with values ranging from <100 to 10,000 m, showing the presence of more small fragments smaller than 100 meters.

According to Niebuhr (2018), the process of the interiority of fragments grows over time. As NVC reduced, there was an increase in the small and irregular remnants in the landscape (see from 2015 onwards in Figure 5c), and this accelerated even more, the edge effect negatively impacting the surviving habitats in the agricultural matrix (Michalski et al., 2008; Benchimol & Peres, 2015).

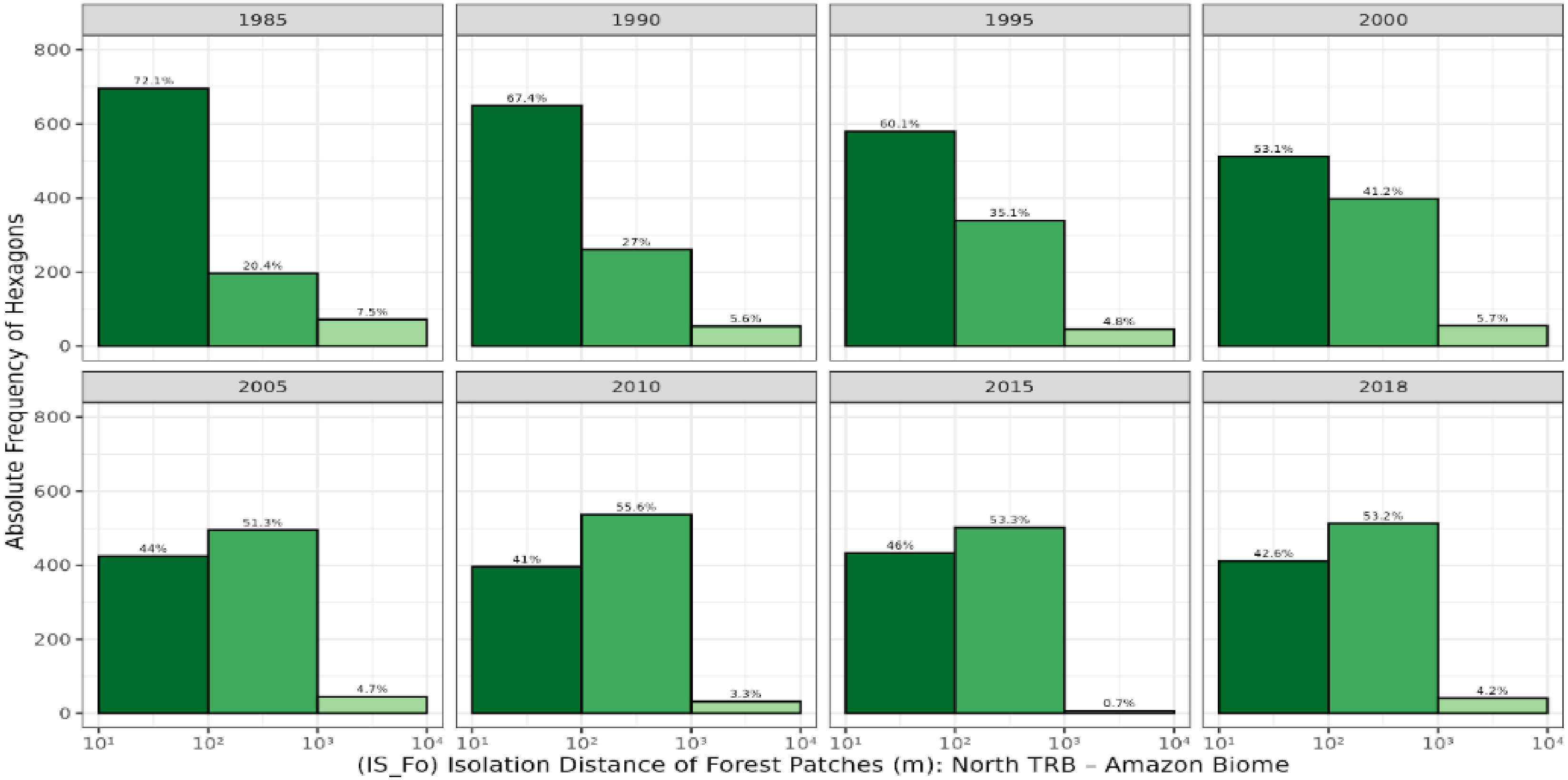
According to Gonzalez et al. (2010), the number of researches has been increasing on the species/area relationship, involving the variables edges and interiors of forest fragments in comparative studies of areas with different species richness. However, according to D'Albertas et al. (2018), these variables in tropical forests can differ significantly depending on the environments and floristic structures sampled. These issues were discussed by Haddad et al. (2015) when comparing the species/area relationship in forest remnants in Africa, Asia, and Amazon.

The adverse effects of small and irregular patches on Neotropical Forest landscapes and edge/interior interactions of these remnants with local species richness were studied – in the Amazon biome by Rosa et al. (2017) and Laurance et al. (2018) and in the Atlantic Forest biome by Pardini (2004) and Ribeiro et al. (2009).

Figure 5d shows the interiorization of savanna fragments in the southern portion of the basin, showing that in the eight analyzed scenarios, the fragmentation process was already established before the studied period, with the presence of small fragments dispersed in the landscape in all analyzed scenarios. This can be observed since 1985 at the beginning of the study, with many small fragments of savannas with interior distances >10 and <1000 meters. At the end of the period, in 2018, the interiorization of the most significant fragments decreased, and the smallest ones increased again, showing a trend of interior loss in all savanna remnants. This is marked from 2015 onwards, the more significant presence of small fragments with internal values smaller than 10 meters, which may indicate the indiscriminate use of savanna formations in the south of the basin (Dros, 2004; Flach et al., 2021). Another possibility is errors in the reading of data from Landsat optical sensors, related to the limitation of the spatial resolution of 30 meters on the ground (Broadbent et al., 2008; Diniz et al., 2015).

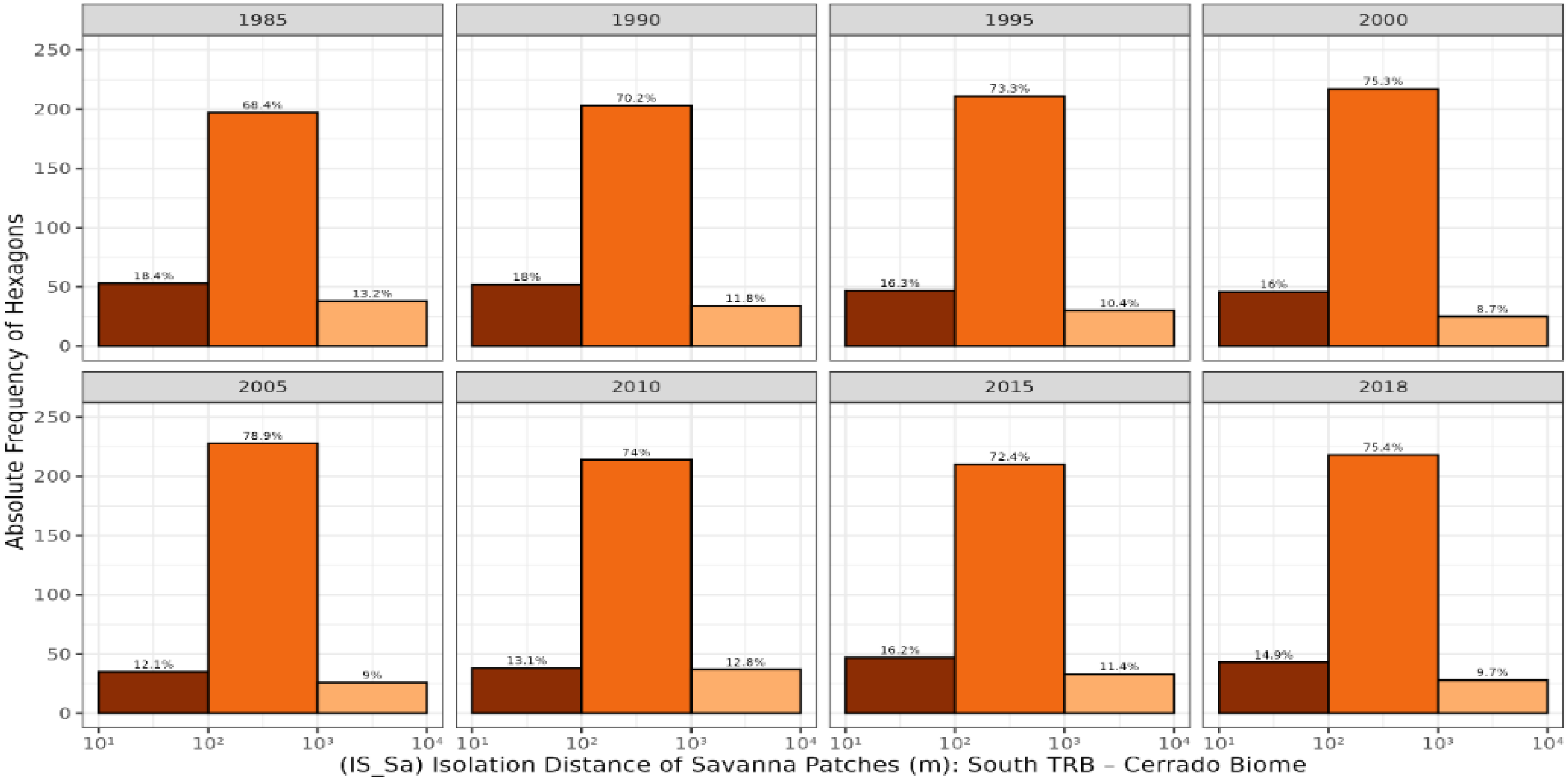
Thus, the generalized presence of small fragments was predominant in the entire southern portion, greatly surpassing the dynamics observed in the northern portion. This effect subjected the Cerrado biome remnants to the largest and longest edge effects recorded in the entire TRB, with drastic effects on the biota and environmental services of Tapajos headwaters (Carvalho et al., 2009; Latrubesse et al., 2019). The articles on edge effect, habitat loss, and isolation in seasonal forests of Cerrado by Klink & Machado (2005), Dodonov et al. (2013), Muylaert et al. (2016), Leal-Melo et al. (2017) corroborated the present study of Tapajos River basin. However, issues related to edges and interiors are complex to be interpreted in tropical forest remnants and often require specific metrics developed for this purpose, as demonstrated by Vieira et al. (2018). For this reason, we used the "Interiority" metric to explain the differences between edges, interiors, and formats of TRB remnants.

Figure 5 (a) - Histograms show on axis (X) the isolation distance between forest fragments and on axis (Y) the absolute frequency of: (a) hexagons (n = 965) in the northern portion of the basin, Amazon biome.



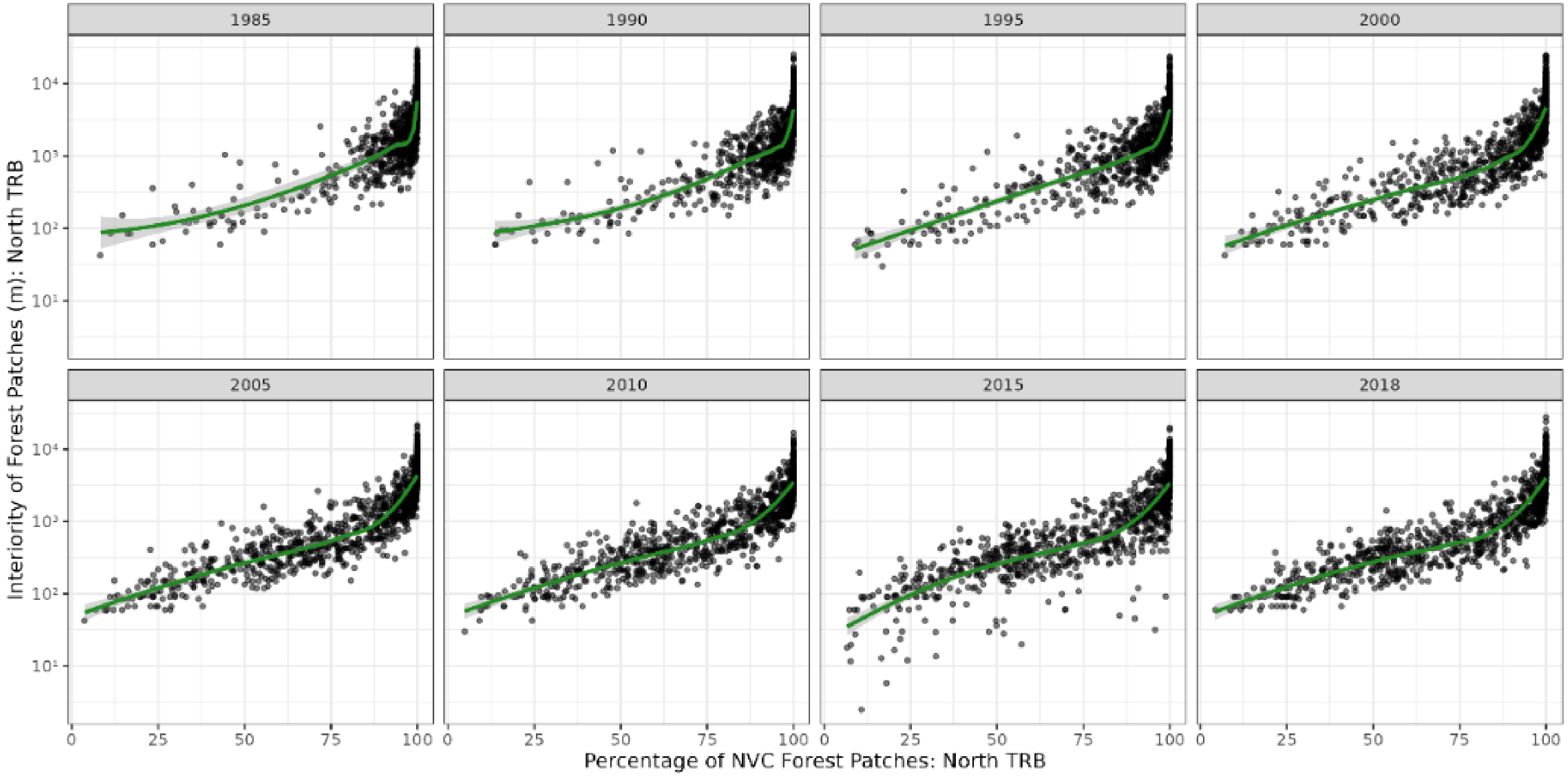
Source: Authors.

Figure 5 (b) - Hexagons (n = 290) in the southern portion of the basin, Cerrado biome. For the period from 1985 to 2018. The interiority of forest fragments concerning the total percentage of: (c) forest fragments in the northern portion of the basin; (d) savanna fragments in the southern portion of the basin.



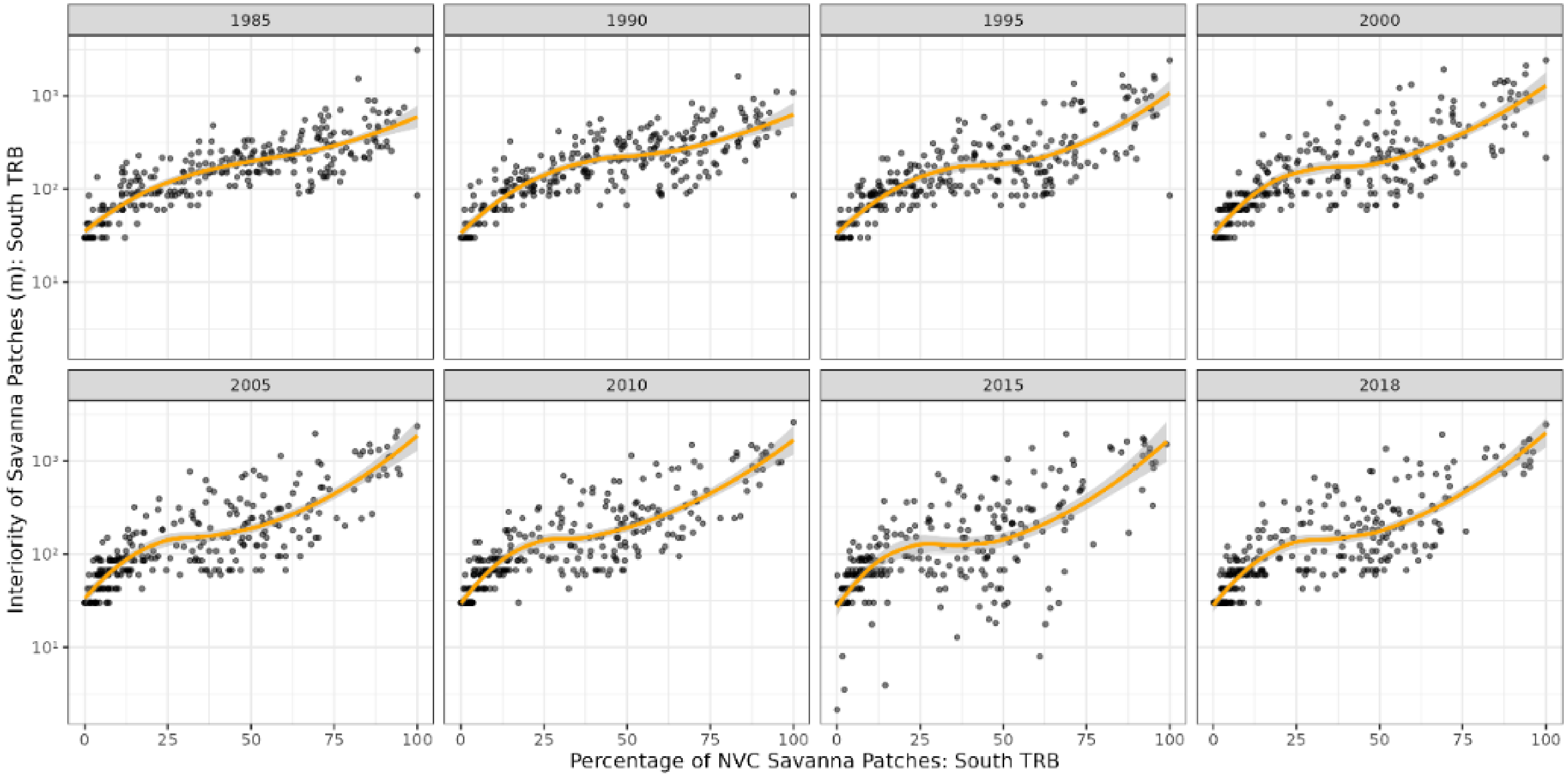
Source: Authors.

Figure 5 (c) - forest fragments in the northern portion of the basin.



Source: Authors.

Figure 5 (d) - savanna fragments in the southern portion of the basin.



Source: Authors.

3.6 Metric – Total percentage of remaining forests and savannas (RE) in the entire TRB area

The figure below shows the maps of TRB divided into the northern portion (Green), which comprises the Amazon biome, and the southern portion (Orange) of the Cerrado biome. The green-toned hexagons on the north portion of the basin show the percentage of NVC reduction (all forest fragments and savannas together) in the hexagonal areas (n = 965) of the Amazon biome. The dark green hexagons represent the highest percentages of NVC (80 to100%), and the lighter green ones represent those with the lowest coverage rates (0 to 20%). The orange-toned hexagons of the southern portion of the basin (n = 290) show a reduction in the percentage of NVC (forests and savannas together) in the Cerrado biome, with the darker orange hexagons indicating the highest rates of NVC (80 to100%) and the lighter oranges with lower percentages of coverage (0 to 20%).

Figure 6a shows the spatial evolution of the loss of NVC in the grid of hexagons within the basin. The lighter hexagons represent the classes with the lowest percentages of coverage, and these were dominant in the southern portion of the basin in all raster maps since 1985. While in the northern part of the basin, the anthropization process with the loss of NVC appears later to be more visible in the grid from 2000. There were not many studies related to cover losses showing the increase of small remnants of arboreal savannas in the Cerrado biome; however, Jepson (2005), Carvalho et al. (2009), and Marques et al. (2020) drew attention to the fact of the increasing loss of these remnants in Cerrado biome, the results found by the authors corroborate the data on the loss of savannas in the southern portion of TRB. These studies proved that large masses of seasonal semideciduous and deciduous forests in the Cerrado biome are quickly converted into small fragments in the transition from Cerrado-Amazon biomes (Silvério et al., 2013) in southern Amazonia.

Figure 6b shows the absolute frequency of hexagons on the Y and X axes and the total percentage of NVC losses in the northern portion of TBR. In 1985, approximately 93% of cover in the hexagonal grid was observed to be intact (80 to 100%), and in the following years, this class of hexagons was gradually lost from 72% in 2000 to about 55% in 2018. However, the lower classes of 20 and 80% of coverage grew in the landscape, showing a general loss of NVC. They went from 7% in 1985 to 42% in 2018. That is, there was a significant loss of all remnants (Fo+Sa) of NVC in the northern portion of the basin. 80 to 100% of the class with the highest coverage dropped by 38% in the hexagon grid from 1985 to 2018.

Figure 6c shows the loss of all remnants (Fo+Sa) of NVC analyzed in the hexagonal grid of the southern portion of the basin. The most significant losses occurred between 1985 and 2005. The class of hexagons with 80 to 100% of intact NVC lost 37% of savannas within the Cerrado biome. Meanwhile, the minor categories of hexagons with 20 to 80% coverage increased in these 20 years, demonstrating a progressive loss of coverage. In the second period from 2005 to 2018, which lasted 13 years, the variations observed between all classes of coverage considered varied very little in the period, the class from 80 to 100% fell by 4%, and the other classes from 20 to 80% practically did not change in these 13 years of study. This fact can be attributed to the reduction of deforestation from 2005 to 2018 and the reduction of fragmentation due to greater environmental control. However, considering the 33 years of the study, the decrease in remnants was more significant in the southern portion of the basin, with 41% of habitats lost.

Reviewing the total habitat losses recorded for the basin area, the northern portion of Amazon biome lost 38%, and the southern portion of the Cerrado biome lost 41% of all remaining forests and savannas in TRB alone. Considering the biodiversity losses in both studied biomes, we draw the readers' attention to the 41% of casualties recorded in the Cerrado biome. Myers et al. (2000) and Mittermeier et al. (2004) are the only significant biological diversity hotspots in southern Amazonia. Most of these remnants were quickly converted, most likely, from 1975 to 1985, into pastures for extensive livestock and crops for annual crops of soybean and corn (Soterroni et al., 2019; Picoli et al., 2020).

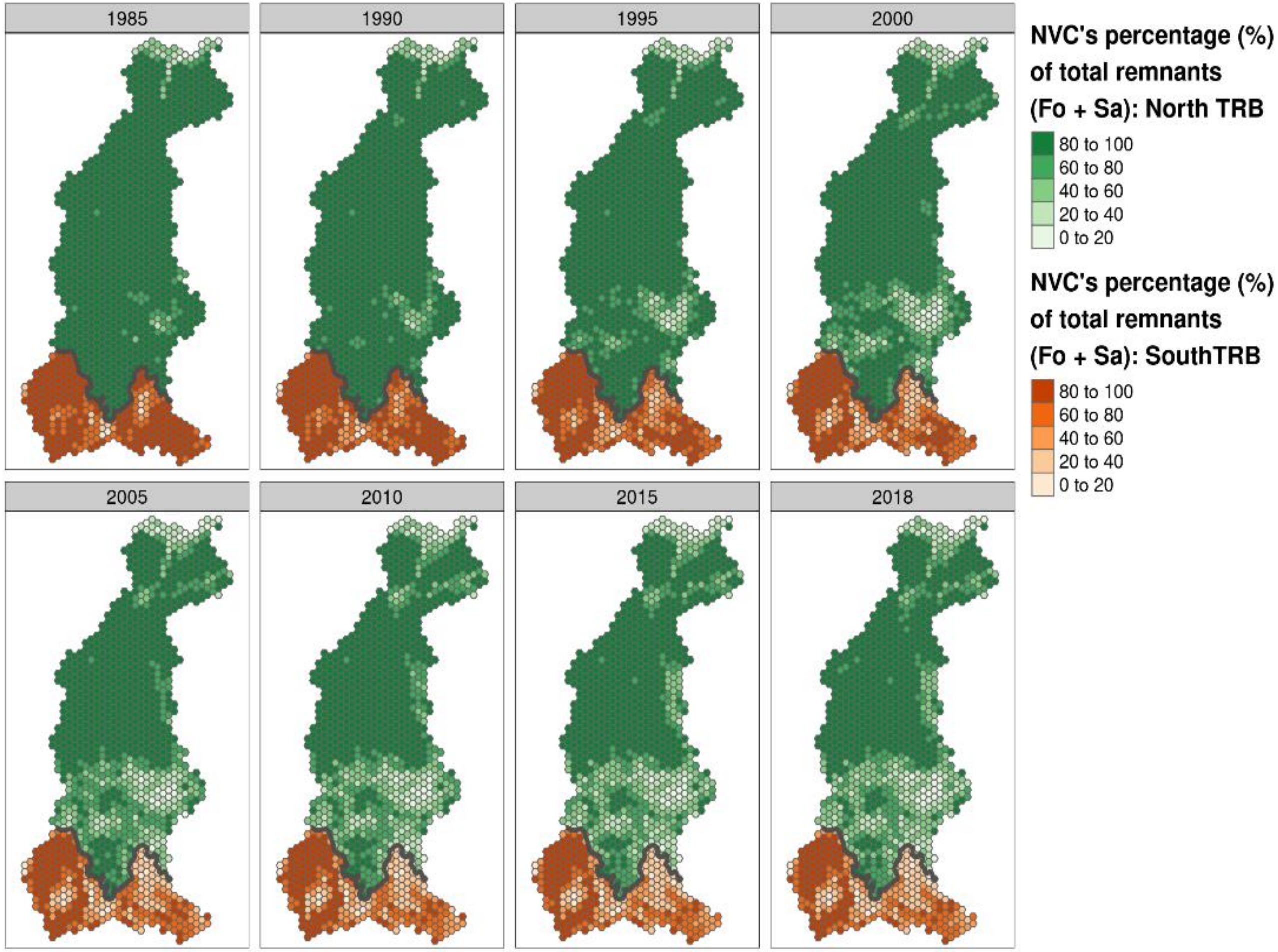
Nepstad et al. (1999) and Fearnside (2005) warned that the agricultural use practiced in the late 1990s for the indiscriminate expansion of soybeans and cattle ranching in southern Amazonia would cause irreparable losses in many megadiverse plant formations. The exploratory model of the Amazonian agroecosystem (extensive livestock – annual farming – logging) still practiced in the region has been questioned as a low conservationist agricultural practice (Defries & Rosenzweig, 2010), resulting in areas of low agricultural production with large NVC losses (Perfecto & Vandermeer, 2008).

Comparing the maps in Figure 6a that show the loss of habitats and the total remaining variables (RE%) in Tables 1 and 2, we see that the lighter hexagons represent the most anthropized and occupied areas in Cerrado and Amazon biomes and correspond to the deforested remnants of NVC. The lighter green and orange hexagons in the landscape represent the areas that have been converted into pastures, crops, urban areas, and infrastructure in general along BR-163, between the cities of Nova Mutum in the plateau, Alta Floresta in the depression, and Itaituba and Santarem in the plain of the lower Tapajos River. So, all those lighter-toned hexes seen on the maps are 38 and 41% of remnants lost on the TRB.

Today, the idea that habitat loss negatively affects biodiversity prevails in academies that study landscape ecology. However, issues involving discussions about habitat loss and its consequences for the planet's threatened forest ecosystems are still premature and very controversial. Fahrig (2017) showed that there was evidence that fragmentation and habitat reduction in forest ecosystems can be beneficial for biodiversity. However, Fletcher et al. (2018) refuted Fahrig (2017) arguments when the authors presented six justifications contesting the author mentioned above's conclusions and stated that the evidence raised was not robust enough to be generalized and taken as a basis for conservation decisions in fragmented landscapes. Discussions about habitat loss generated by fragmentation are starting, and this effect on the ecology of Neotropical landscapes is new and needs more field evidence (Vieira et al., 2018; Püttker et al., 2020).

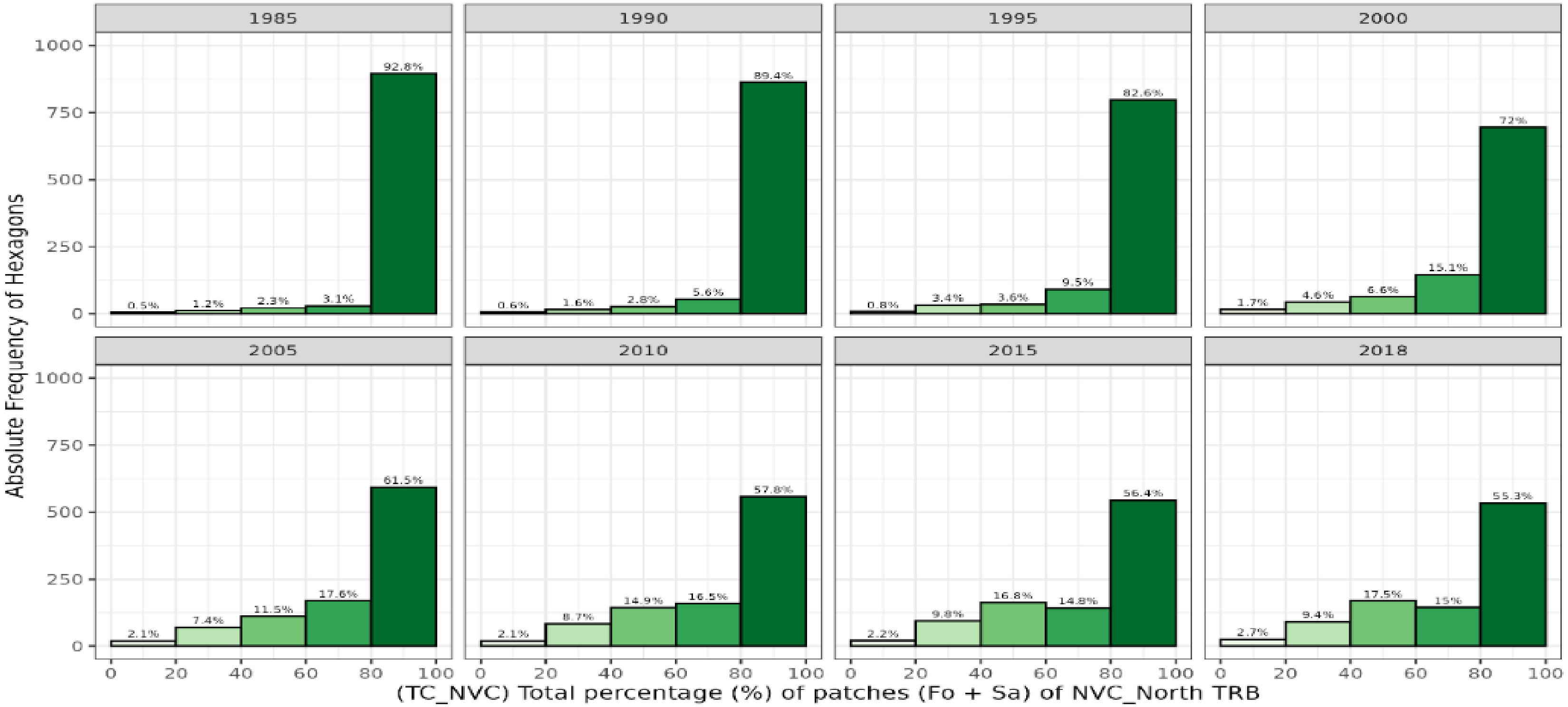
Finally, it is essential to recognize that the total habitat loss was significant in TRB and occurred in a relatively short period of the history of Amazonian occupation (Margulis, 2003 and Alencar et al., 2004). Therefore, while there is no critical review of the current exploratory model of the regional agroecosystem, environmental control measures are not adopted, and the percentage of loss of 40% of the vegetation remains at the current level. The prognosis for 2040 is not encouraging when probably 60% of NVC will be converted into anthropic areas (Lees et al., 2016 and Latrubesse et al., 2017), severely compromising biodiversity and the hydrological cycle in the basin (Soares-Filho et al., 2006 and Nobre et al., 2016). This scenario is not far from happening, as evidenced by the fragmentation and habitat loss studies carried out in the transition of the Cerrado – Amazon biomes (Montibeller et al., 2020 Flach et al., 2021). The current agenda and demand for habitat fragmentation research are more focused on hypotheses related to the amounts of habitats that must remain in modified landscapes to ensure gene flow between metapopulations in the remnants of NVC (Fahrig, 2013 and Joly et al., 2014).

Figure 6 (a) - TRB maps and the compartmentalization of Cerrado and Amazon biomes, showing in the grid of hexagons (green, n = 965 - Amazon and oranges, n = 290 - Cerrado biomes) the evolution of fragmentation and the percentage of loss of the total remaining forests and savannas between 1985 and 2018. On X axis is the percentage of reduction of all remnants (Fo+Sa) of NVC, and on Y axis is the number of hexagons with the fragments sampled in the: (b) northern portion of TRB; (c) southern portion of TRB.



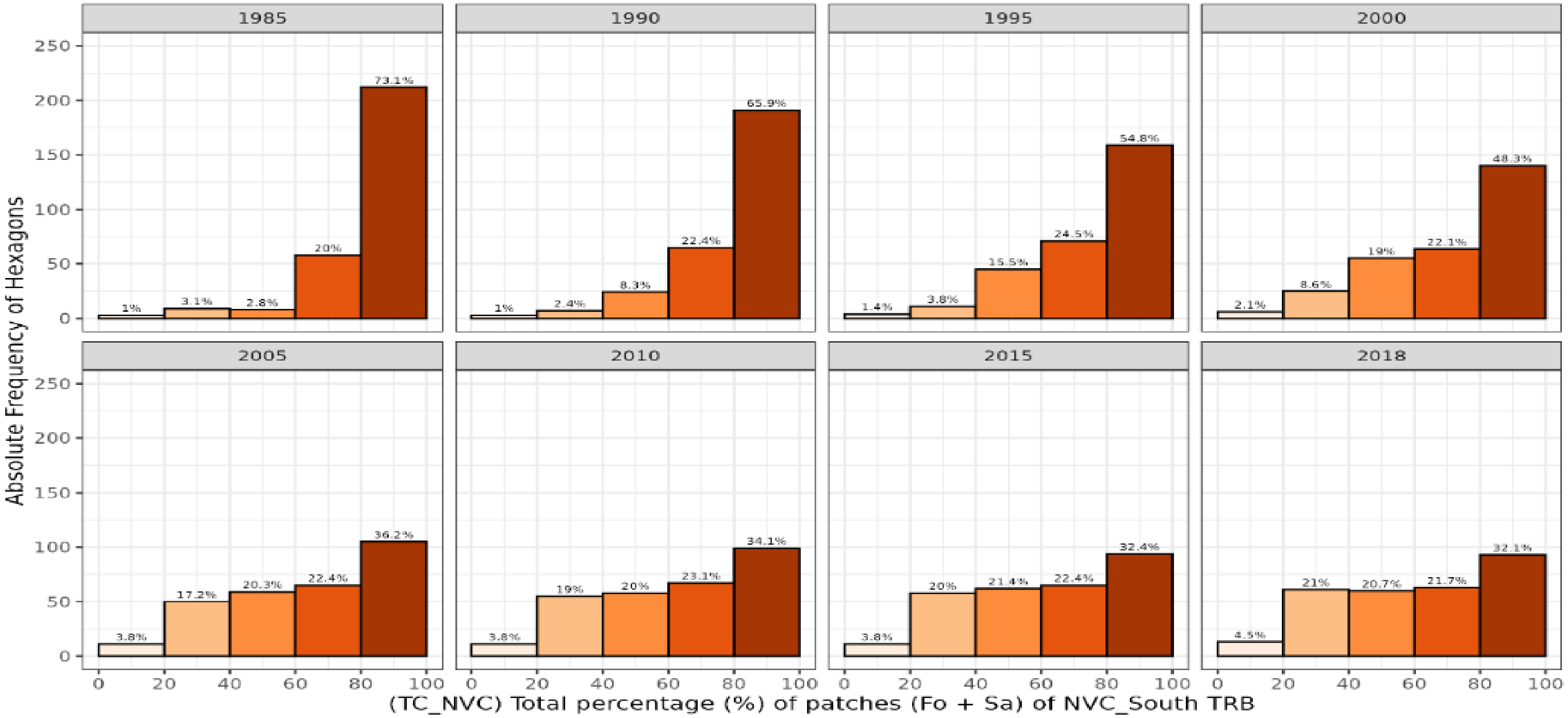
Source: Authors

Figure 6(b) - Northern portion of TRB.



Source: Authors.

Figure 3 (c) - southern portion of TRB. For the period from 1985 to 2018.



Source: Authors.

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3.7 Hypotheses raised – events of fragmentation in TRB

3.7.1 Principal component analysis – Amazon biome

Based on the results obtained by the principal component analysis (PCA), the respective values of the variance retained in each of the components are shown in Figure 7a.

It is observed that the main components 1 and 2 correspond to the dimensions with the maximum variation in the data

dimensions. According to Jolliffe (2002), models that present values above 70% of the total variation effectively summarize the sample variance and can be used to study the data set.

After defining the main components, a factorial map was generated, showing in Figure 7b the groups of the most correlated landscape metrics in the analysis of the northern portion of the TRB.

Note that positively correlated metrics were grouped, while negatively correlated metrics were positioned on opposite sides of the origin of the factor map. In addition, the distance between the metrics and the origin measured the quality of the representation. That is, the further they were from the origin, the more significant the contribution of the metrics on the map (Jolliffe, 2002).

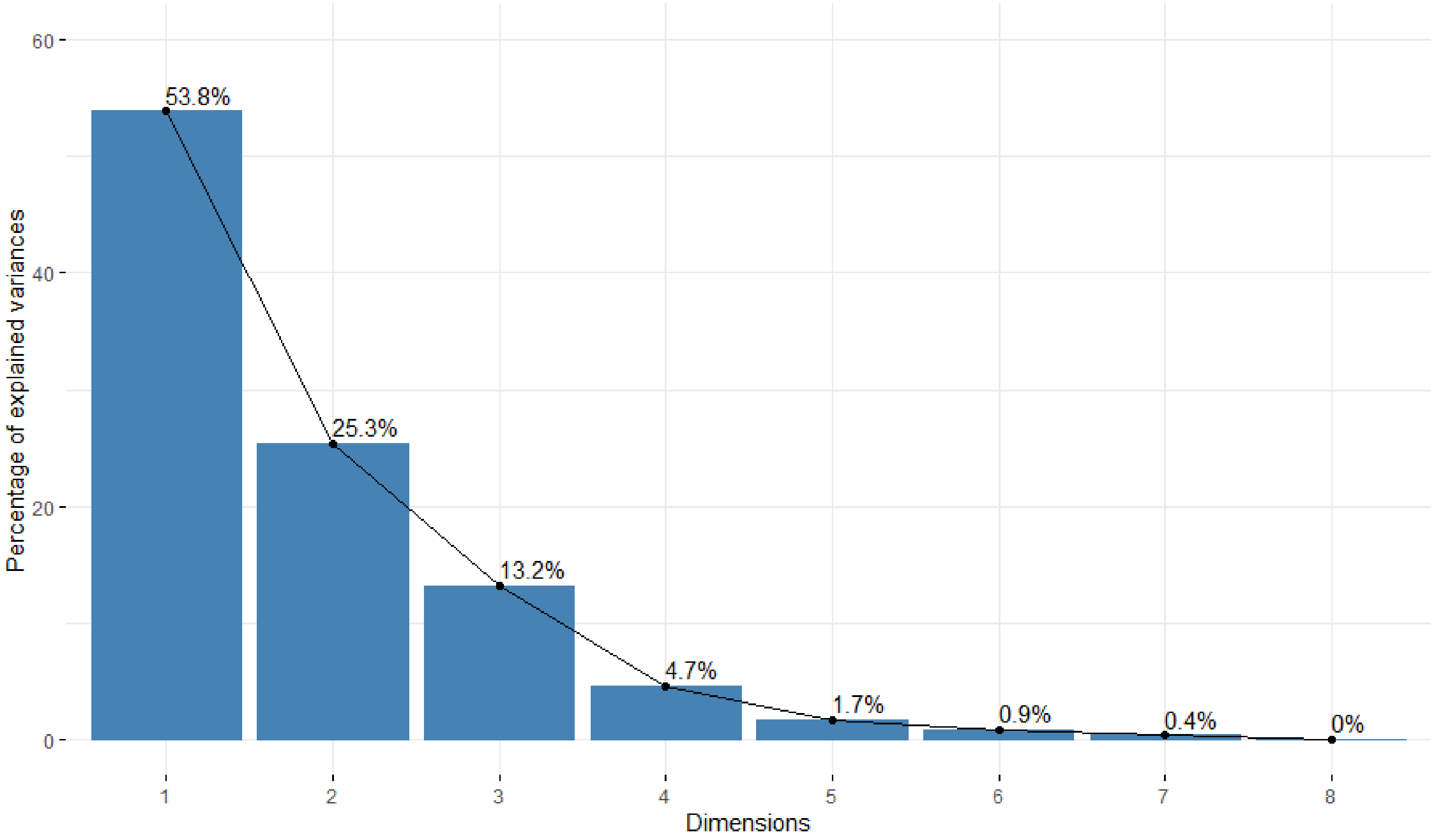
Metrics that were correlated with principal component 1 (i.e., Dim.1) and main component 2 (Dim.2) were the most important for explaining variability in the dataset. Conversely, metrics that did not correlate with any of the chosen dimensions were variables of low contribution and could be disregarded to simplify the general analysis (Jolliffe, 2002). Therefore, the ISS metric was poorly represented as it had a low contribution value for the chosen principal components.

In Figure 7b, the metrics can be grouped into clusters: group (I) number of forest patches (NPF), edge of forest patches (EDF), the interior of forest patches (INF), and (II) area of forest patches (PSF), forest remnants (REF), isolation of forest patches (ISF) were positively correlated metrics. In contrast, metrics from the group (I) were negatively correlated with group (II). Furthermore, group (III) edge of savanna patches (EDS) and savanna remnants (RES) were positively correlated metrics. In contrast, the interior of savanna patches (INS) and the area of savanna patches (PSS) were negatively correlated.

Figure 7c is a composite of the metrics used with the sampled periods. It is noteworthy that in the biplot chart, the focus is on the direction of the metrics but not on their absolute positions on the chart (Jolliffe, 2002).

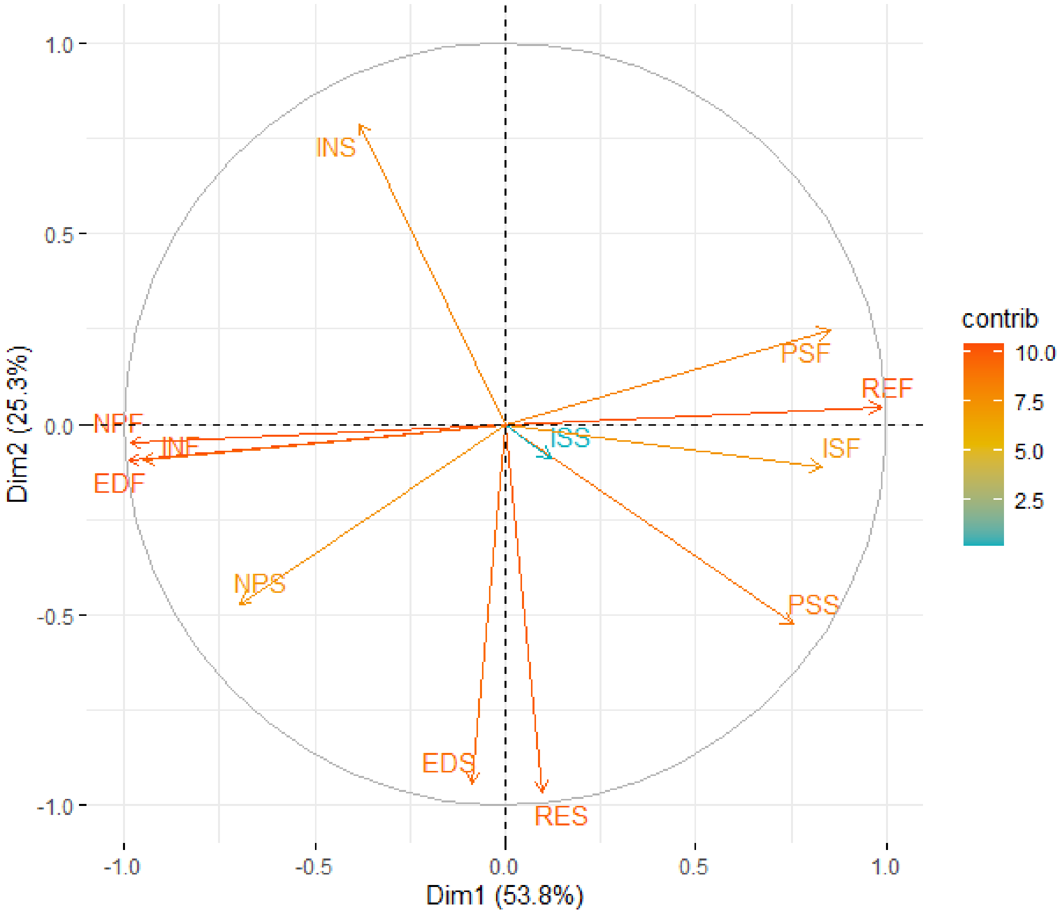
Periods on the same side of a given metric indicated a high value for that variable. In contrast, a period on the opposite side of a metric had a low value for that variable (Jolliffe, 2002). It is inferred, then, that NPF, EDF, and INF had their highest values in 2018, showing that these metrics explained the fragmentation that occurred in the period. Likewise, the metrics PSF, REF, and ISF better characterized the fragmentation between 1985 and 1995. Finally, the metrics EDS and RES had their highest values in 2005.

Figure 7 (a) - Variance explained by dimension.



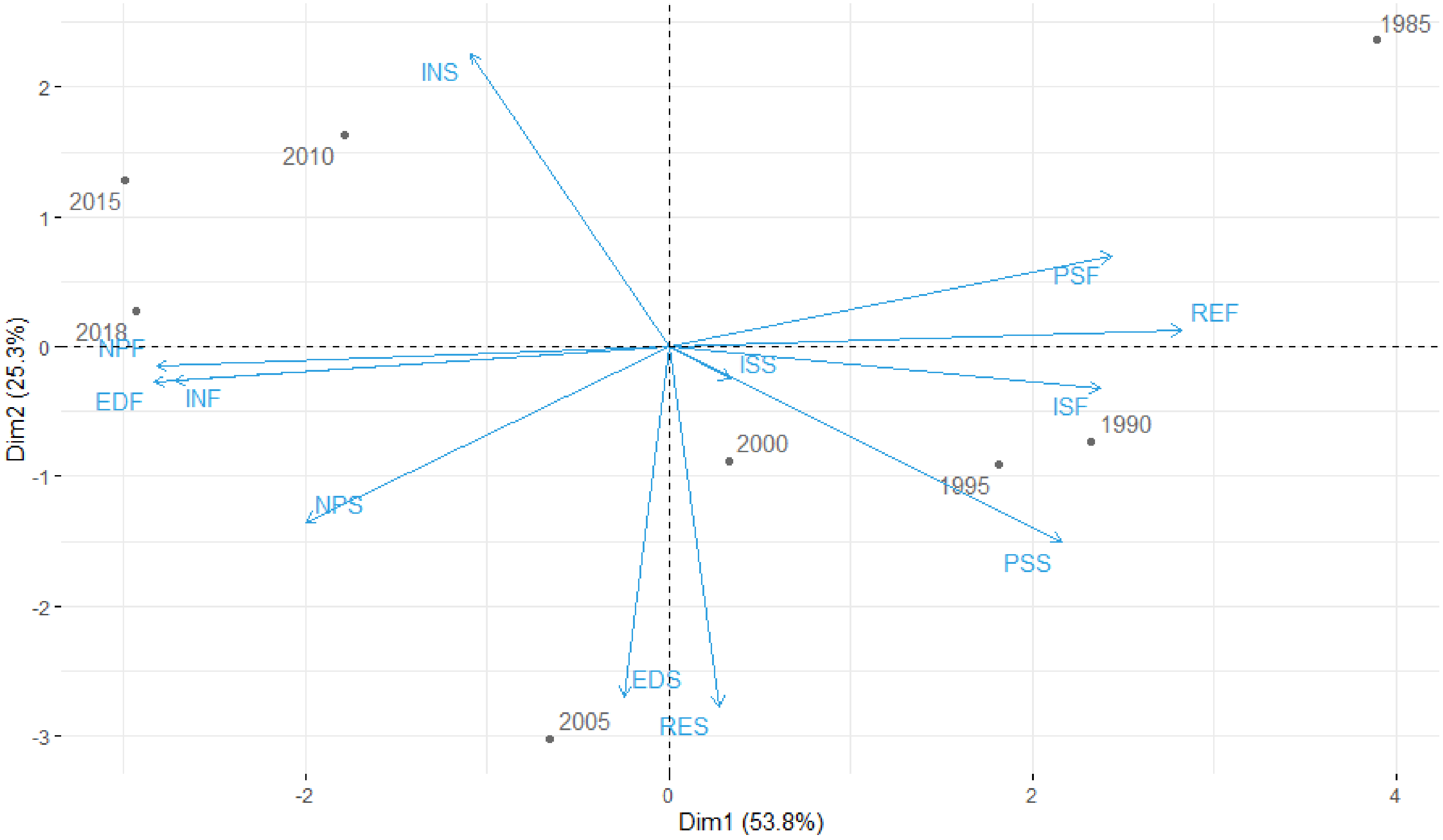
Source: Authors.

Figure 7 (b) - Factorial map of landscape metrics.



Source: Authors.

Figure 7 (c) - Biplot of sampled metrics and periods. NPF= Number of Forest Patches, PSF= Size of Forest Patches, EDF= Edge of Forest Patches, INF= Interior of Forest Patches, ISF= Isolation of Forest Patches, REF= Forest Remnants. NPS= Number of Savanna Patches, PSS= Size of Savanna Patches, EDS= Edge of Savanna Patches, INS= Interior of Savanna Patches, ISS= Isolation of Savanna Patches, RES= Savanna Remnants.



Source: Authors.

3.7.2 Principal component analysis – Cerrado biome

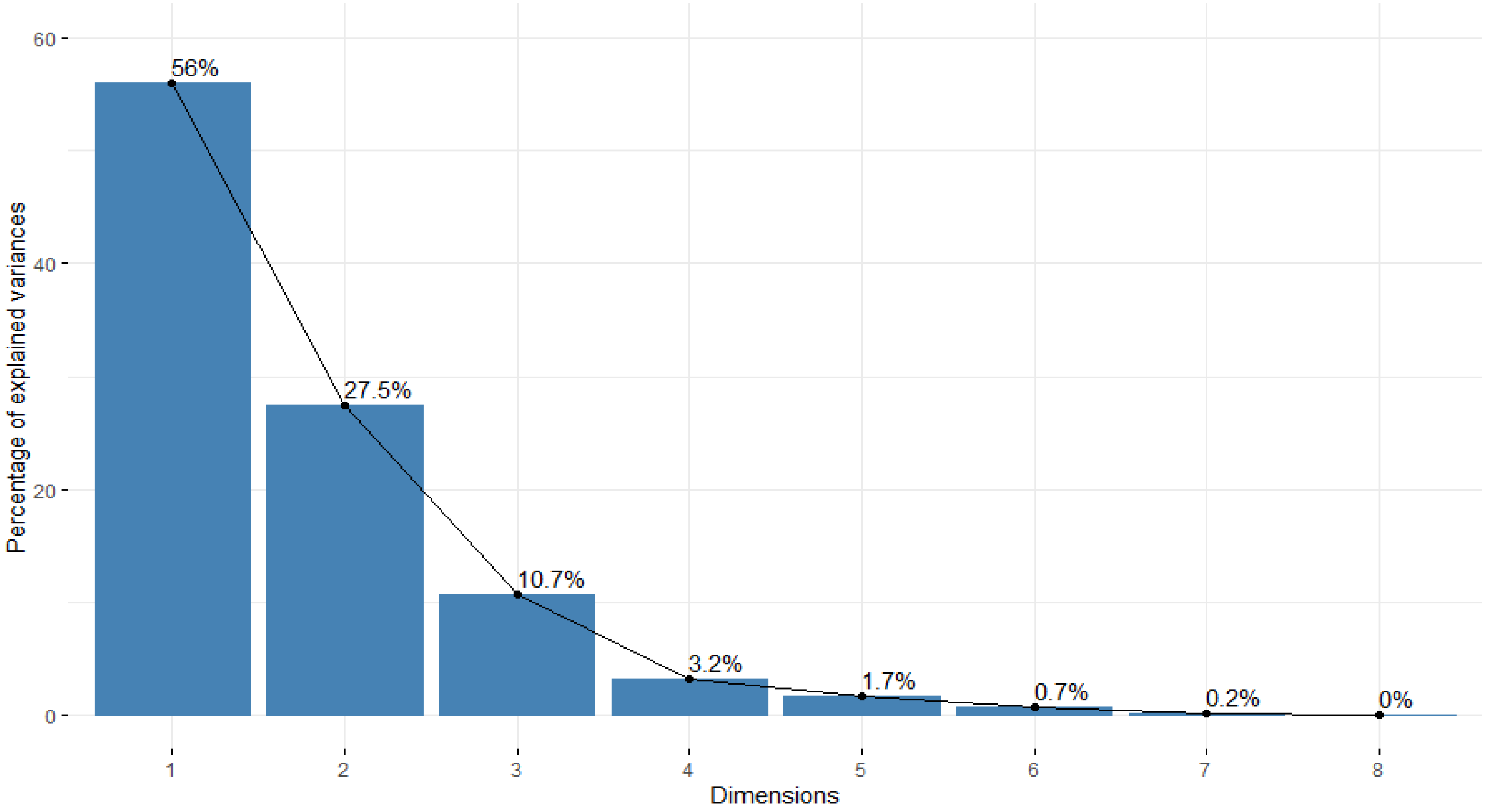
Based on the results obtained by the PCA, the respective values of the variance retained in each component are shown in Figure 8a.

It is observed that the first two principal components explained 83.5% of the total variance in the southern portion of TRB (Cerrado), meeting the criterion presented by Jolliffe (2002). Therefore, the factor map shown in Figure 8b was generated after defining the main components.

Thus, in Figure 8b the metrics could be clustered: the groups (I) RES, PSS, and EDS; (II) REF and PSF; (III) NPF and EDF were the groups of positively correlated metrics. In group (II), REF and PSF were negatively correlated with the INF metric, and group (I) metrics were negatively correlated with the NPS metric. In group (III), EDF and NPF were negatively associated with the ISF metric. In addition, it is possible to observe that the INS metric was not well represented because it had a low contribution value for the chosen principal components.

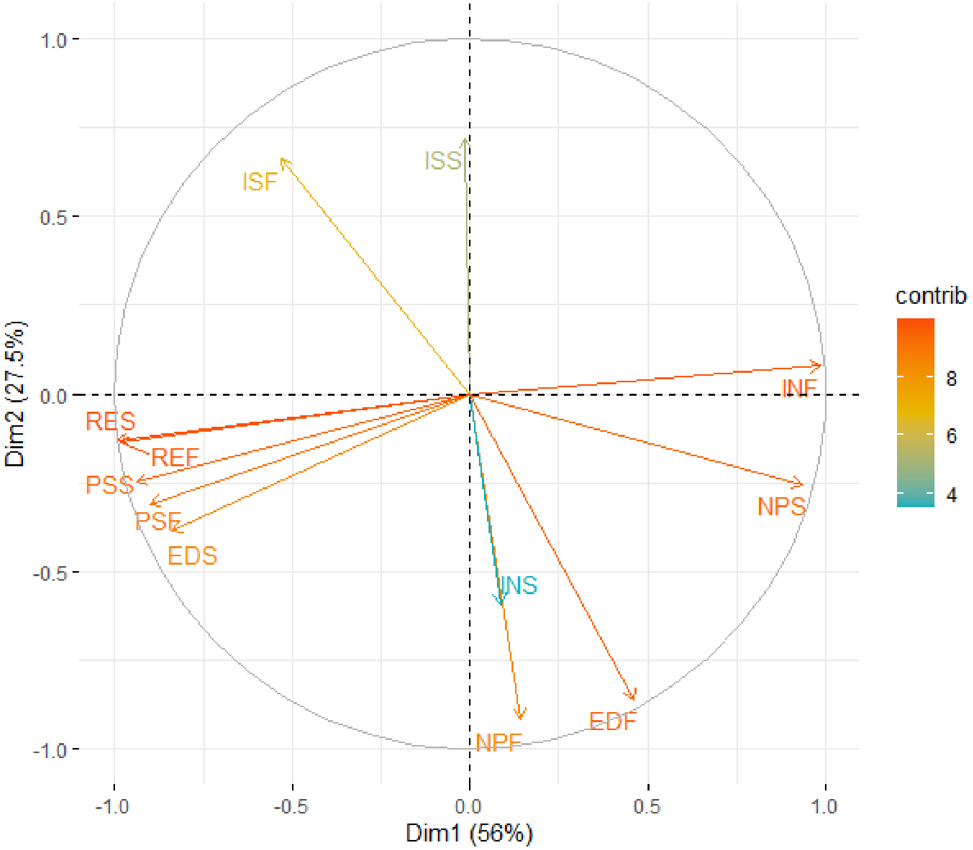
Figure 8c shows the Biplot graph, in which it was inferred that RES, REF, PSS, PSF, and EDS had their highest values between 1985 and 1990, showing that these metrics explained the fragmentation that occurred during the period. Likewise, the ISF and ISS metrics best characterized fragmentation in 2000. Finally, the INF and NPS metrics had their highest values in 2015 and 2018.

Figure 8 (a) - Variance explained by dimension.



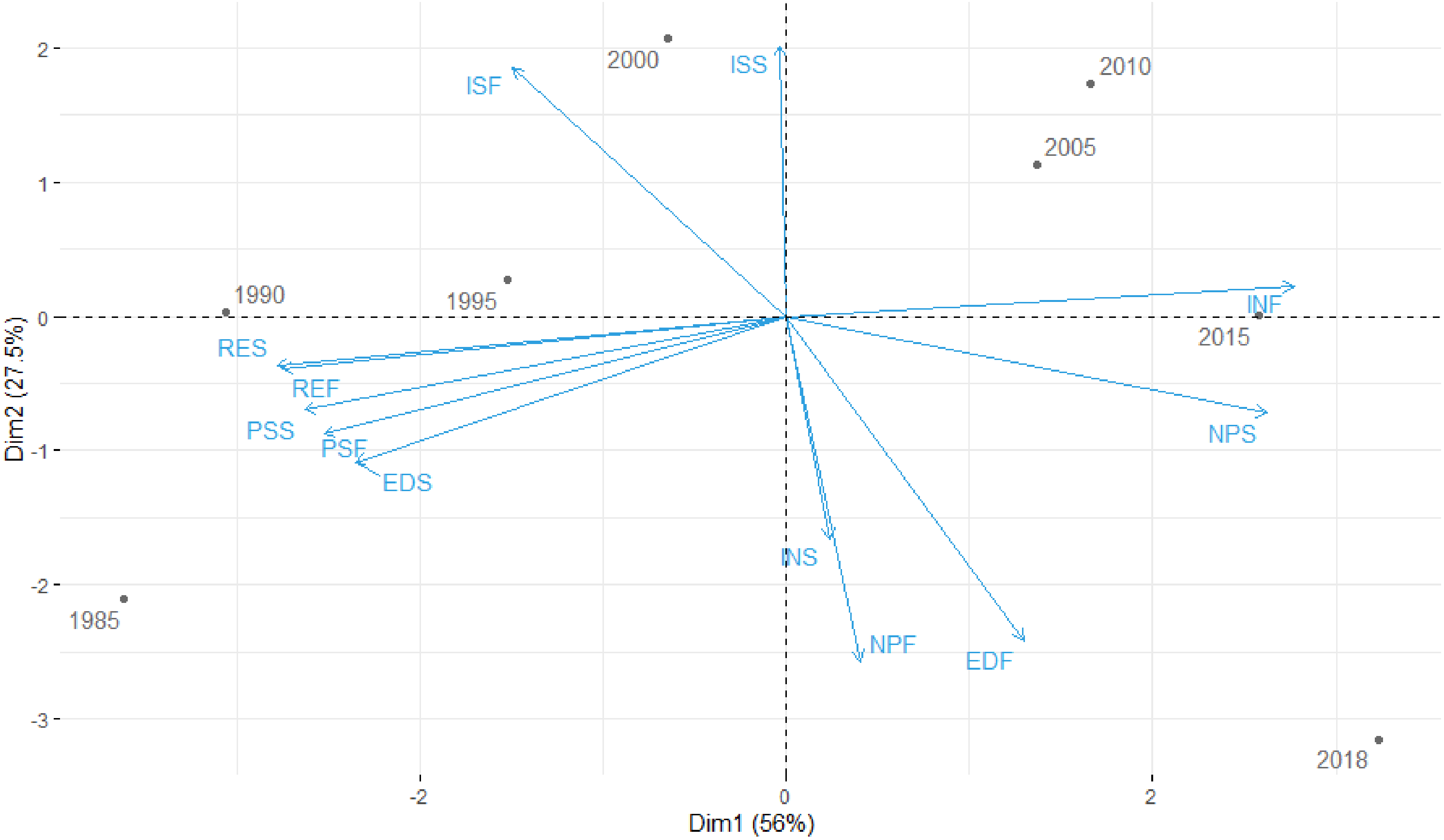
Source: Authors.

Figure 8 (b) - Factorial map of landscape metrics.



Source: Authors.

Figure 8 (c) - Biplot of sampled metrics and periods. NPF= Number of Forest Patches, PSF= Size of Forest Patches, EDF= Edge of Forest Patches, INF= Interior of Forest Patches, ISF= Isolation of Forest Patches, REF= Forest Remnants. NPS= Number of Savanna Patches, PSS= Size of Savanna Patches, EDS= Edge of Savanna Patches, INS= Interior of Savanna Patches, ISS= Isolation of Savanna Patches, RES= Savanna Remnants.



Source: Authors.

3.7.3 Cluster analysis – Amazon and Cerrado biomes

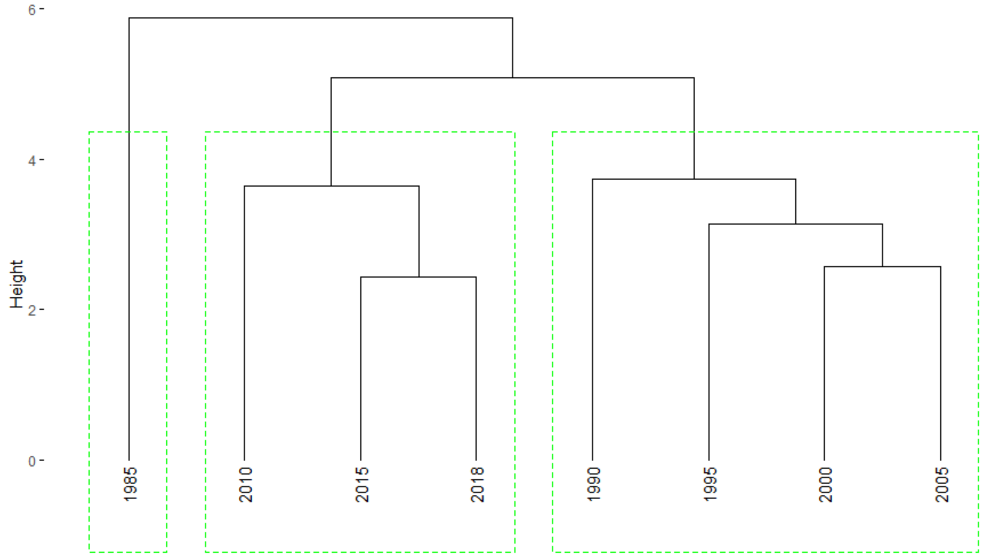
Initially, the cluster analysis was performed using the similarity coefficients of the Euclidean distance, with the hierarchical clustering representation through the dendrogram image, presented below in Figure 9. Then, the indicators of the NbClust function were used to assist in choosing the number of ideal groupings (Kassambara, 2017). Thus, the optimal number of clusters obtained for the Amazon biome was 3, as shown in Figure 9a. Likewise, in Figure 9b for the Cerrado biome, the ideal number of clusters was 4.

The agglomerative hierarchical clustering was obtained through an algorithm capable of providing more than one type of data partition, where a cluster could be merged with another in a specific step of the algorithm, not being necessary to have an initial number of defined sets. On the other hand, with the Kmeans clustering (non-hierarchical), it is essential to determine an initial partition, characterized by its flexibility, since the analyzed years could be grouped during the algorithm's execution (Anderberg, 1973). Thus, from the definition of the number of clusters by the hierarchical method, we ran the second Kmeans clustering method below.

Figure 9c shows the graph generated by the Kmeans method, referring to the optimal number of clusters for Amazon and Cerrado biomes, considering the intra-cluster variance. Thus, using the notion of intra-cluster sum of squares, it was possible to verify that the optimal number of clusters for Amazon Biome was three and for Cerrado Biome was 4. This was because new clusters above these values had low gain to increase differentiation of the other groups (Kassambara, 2017). After determining the ideal number of clusters, it was obtained to which clusters each sampled period belongs, as shown in Figures 9d and 9e.

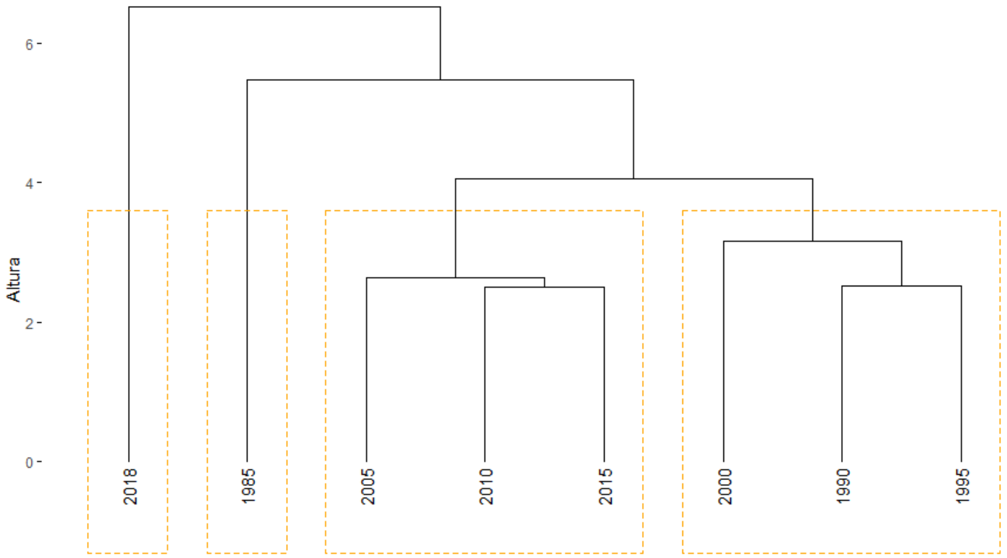
This way, the proximity between the periods sampled in their clusters was evident. We chose to proceed with the analysis using the results obtained by the Kmeans method (non-hierarchical), as it represented a better distribution of the analyzed periods in the Cerrado biome, while for the Amazon biome, the result was the same for agglomerative clustering and Kmeans. Another decisive factor in the choice of Kmeans clustering was its flexibility characteristic (Anderberg, 1973), considering that the method allowed the analysis of each sample period in several clusters.

Figure 9 (a) - Cluster analysis. (a) Groups of periods with similar fragmentation in the northern portion of the TRB.



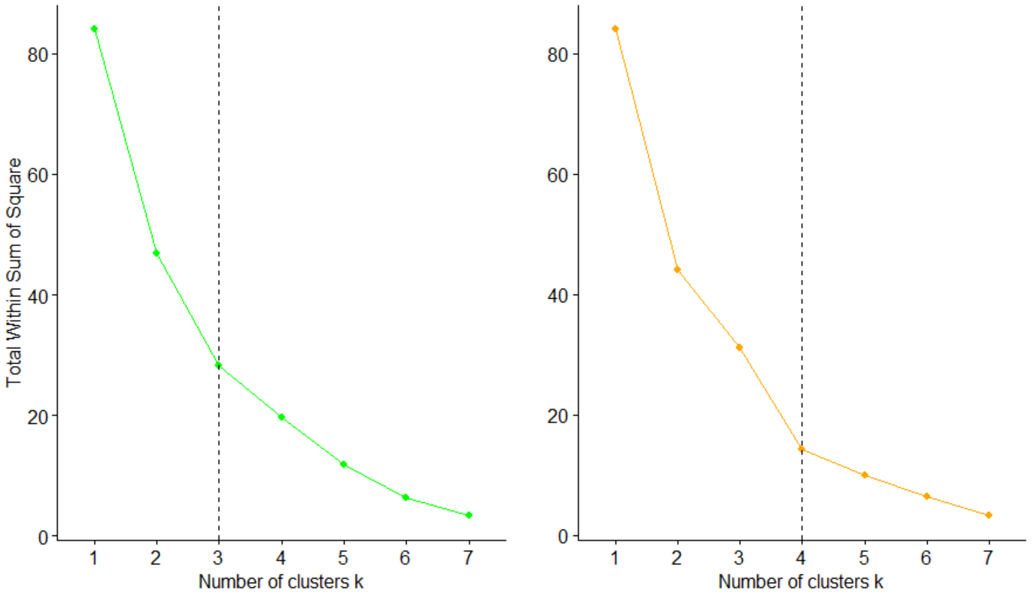
Source: Authors.

Figure 9 (b) - Dendrogram of the Cerrado biome, showing the groups of periods with similar fragmentation in the southern portion of the TRB.



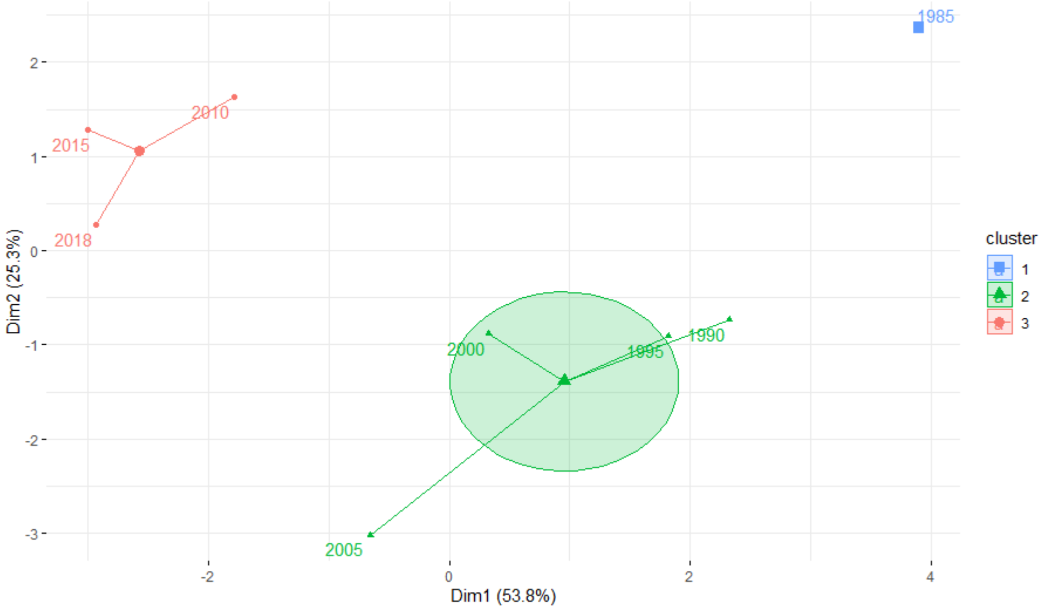
Source: Authors.

Figure 9 (c) - The optimal number of clusters generated by the Kmeans method in the two studied TRB biomes. Groups defined by the Kmeans method for the: (d) Amazon biome; (e) Cerrado biome.



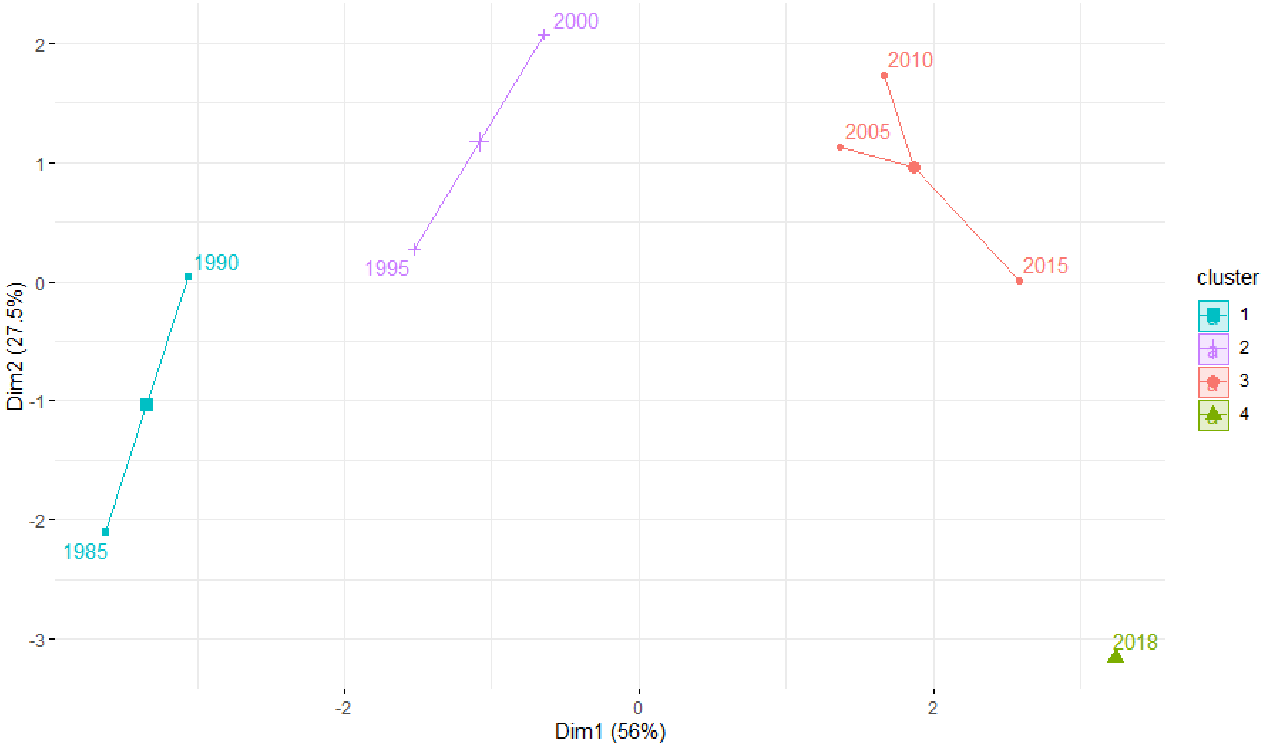
Source: Authors.

Figure 9 (d) - Amazon biome.



Source: Authors.

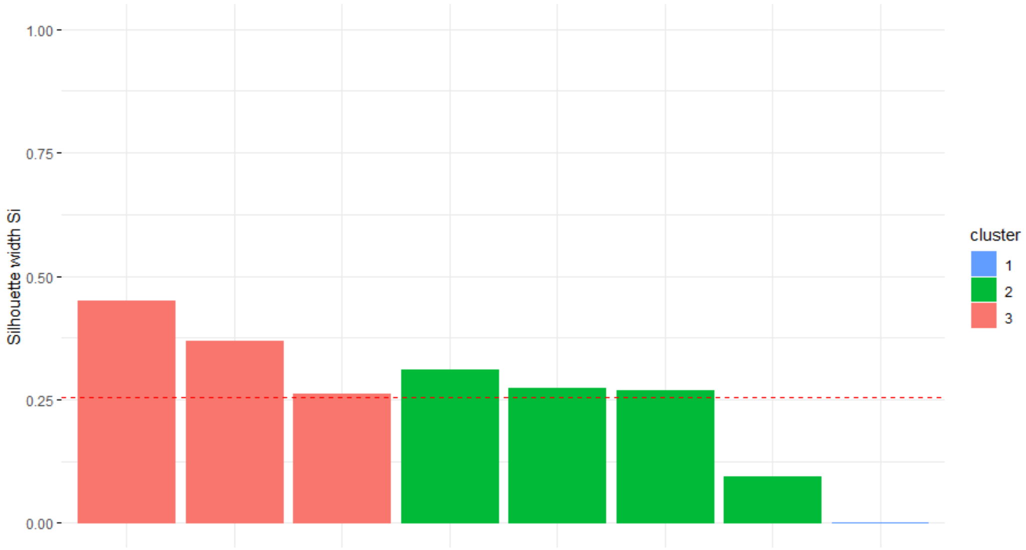
Figure 9 (e) - Cerrado biome.



Source: Authors.

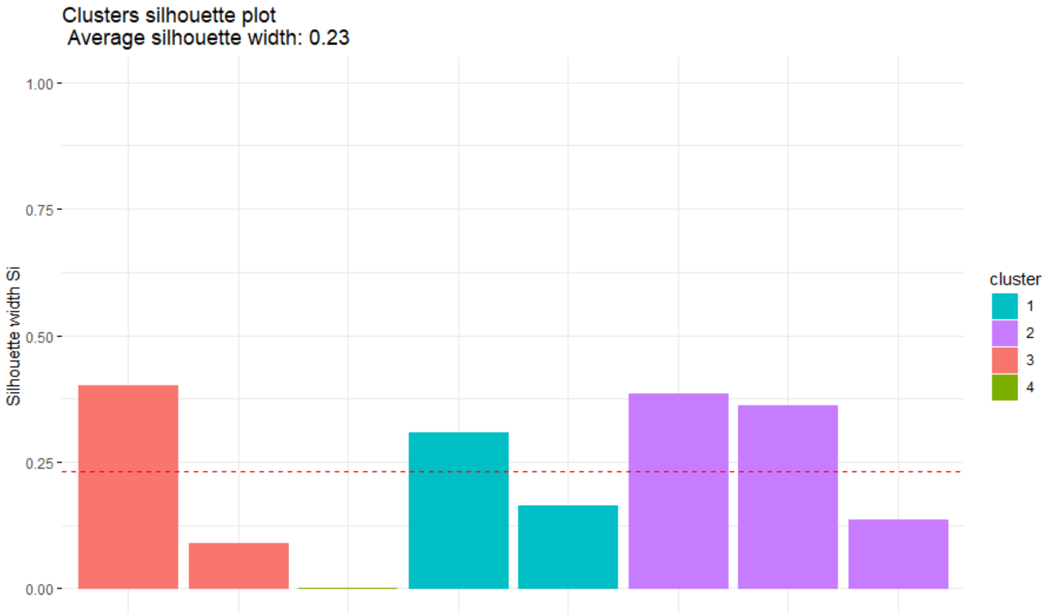
Among the approaches to validate the results of the Kmeans clustering, the Silhouette method developed by Rousseeuw (1987) was used. The silhouette graphic method was composed of a dimensionless number, called silhouette value, representing the quality of the formation of the groups with the analyzed periods. This value varied from -1 to 1, where one means that the considered period was well grouped, while -1 implies that the period was poorly classified and is further away from its group. Therefore, the closer to 1, the better the clustering quality (Rousseeuw, 1987). Figures 10a and 10b show the graphs obtained by the Silhouette method for the Amazon and Cerrado biomes in TRB.

Figure 10 (a) - Graphs obtained by Silhouette method for: (a) Amazon Biome.



Source: Authors.

Figure 10 (b) - Cerrado biome.



Source: Authors.

As a result of the silhouette method, an average silhouette value = 0.25 was obtained for the Amazon biome and an average silhouette value = 0.23 for the Cerrado biome, which was a satisfactory result considering the criteria proposed by Rousseeuw (1987). Furthermore, the groupings were also validated from the interpretation of the average values obtained by the Kmeans method, summarized below in Tables 3 and 4.

Table 3 - Average results of the clusters and the six most significant metrics for the Amazon Biome.

Cluster	**Number Patches (NP)**		**Patches Size (PS, ha)**		**Edge of Fragments (ED %)**		**Interior of Fragments (IN, meters)**		**Fragments Isolation (IS, meters)**		**Remnents (RE %)**	
	Forest	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**
1: 1985	31,71	37,84	44.630.291,72	88,00	1,68	0,24	-3.503,13	-33,22	1.746,19	11.075,32	93,65	0,46
2: 1990 - 2005	63,84	52,82	24.142.918,81	101,26	2,61	0,34	-2.500,32	-34,95	1.232,62	11.171,09	85,85	0,67
3: 2010 - 2018	104,49	55,87	14.078.641,07	56,84	3,51	0,28	-1.768,58	-32,53	636,82	10.774,38	75,88	0,50

Source: Authors.

Table 4 - Average results of clusters and six most significant metrics for the Cerrado Biome.

Cluster	**Number Patches (NP)**		**Patches Size (PS, ha)**		**Edge of Fragments (ED %)**		**Interior of Fragments (IN, meters)**		**Fragments Isolation (IS, meters)**		**Remnents (RE %)**	
	Forest	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**	**Forest**	**Savanna**
1: 1985 - 1990	162,85	215,56	28.236.817,70	485.132,95	4,30	6,15	-453,95	-221,23	730,14	508,72	41,67	42,71
2: 1995 - 2000	156,57	253,98	12.069.154,83	307.127,45	4,24	5,93	-389,78	-243,71	770,04	515,23	38,68	37,16
3: 2005 - 2015	153,06	281,34	7.579.230,40	189.957,31	4,29	5,32	-292,12	-224,07	711,34	518,69	33,77	31,07
4: 2018	186,96	342,00	7.724.164,30	188.520,09	4,67	5,60	-266,57	-223,73	672,83	494,62	33,19	30,06

Source: Authors.

It is possible to verify the characteristics of each grouping of the analyzed periods. With the average values in the Amazon biome (Table 3), it was observed that the lowest values of the metrics NP, ED, and IN were found in cluster 1 (1985), together with the highest importance for the metrics PS, IS and RE. In cluster 2 (1995-2005), there were values of the metrics with the most remarkable similarity since average values were obtained for all metrics. And in cluster 3 (2010-2018), there was the inverse of cluster 1, with the highest importance for the NP, ED, and IN metrics and the lowest values for the PS, IS, and RE metrics.

This was expected in the Amazon biome, considering that the period comprising cluster 1 (1985) was when the most outstanding coverage of native vegetation was in the northern portion of TRB. In this sense, cluster 2 (1990-2005) was the cluster marked by an average fragmentation in the landscapes of the basin. While cluster 3 was characterized by the fragmentation increase that occurred between 2010 and 2018 in the basin's northern portion (Amazon biome) (Soares-Filho et al., 2004; Chazdon & Guariguata, 2016).

Examining Table 4, it is possible to understand the characteristics of the clusters formed by the metrics analyzed in the Cerrado biome, with cluster 1 (1985-1990) being characterized by the lowest values for the NPS and INF metrics and the highest importance for PSF and EDS. Cluster 3 (2005-2015) was characterized by presenting the lowest values for PSF, EDF, REF, and RES, showing a period where fragmentation advanced little in the landscapes of the southern portion (Cerrado biome) of TRB. Meanwhile, cluster 4 (2018) had the lowest values for the PSF/AFS, ISF/ISS, REF/RES metrics and the highest values for NPF/NPS and INF, which characterizes a period where fragmentation grew again in the southern portion from the basin. Finally, cluster 2 (1995-2000) showed a period where fragmentation had an atypical behavior, with average values for all six metrics analyzed in the TRB South compartment.

Analyzing the results of the metrics in Table 4 for the Cerrado biome, the area of the fragments (PS) and the percentage of remnants (RE) in cluster 1 (1985-1990) was the period in which TRB presented the highest NVC. On the other hand, the metric (NP) showed a significant increase in the number of patches from 2015 to 2018 and consequently lost area (PS) in the same period.

Analyzing the reduction in the percentage of the remaining metric (RE) throughout the period (1985-2018), the variation found between the four clusters considered was not so expressive, given that the fragmentation of the landscape in the Cerrado biome was already consolidated in TRB in 1985. When we analyze the result of the metric (RE%) for the typologies of forests and savannas in the Cerrado biome (see Table 4), it is observed in cluster I (1985-1990) that both typologies analyzed had already lost 60 % of their original coverage. Finally, exploring the metric isolation of fragments (IS), it can be observed that it varied very little among the four clusters in the period studied. That is, visually fragmentation was high in the southern portion of TRB. We could not register the effect with the metrics used in the study (Matricardi et al., 2020).

With the evolution of fragmentation in the landscape of the Cerrado biome that the isolation between forest and savanna fragments would increase with time. However, the IS values decreased between the considered clusters (Table 4). The studies presented by Hagen et al. (2012), Fahrig (2013), and Püttker et al. (2020) also drew attention to these variations between the geometry and isolation distance of the remaining endangered forest habitats. When we observe the spatial-temporal changes that occur with the fragments and the oscillations of the distances between the nearest neighbors, at the beginning of the fragmentation the IS increases in the matrix, because the inter-fragment distance increases. However, after a few years of fragmentation, the IS distance decreased because the density of the fragments in the agricultural matrix increased, which reduced the space between the fragments (Fahrig, 2013).

These historical findings on the isolation of forest habitats were described with the remnants of the Atlantic Forest. Initially, the IS increased in the landscape, but after some years of fragmentation, it decreased. Recently it increased again because the density of the fragments in the matrix reduced, thus increasing the distances isolation (IS) between the matrix fragments (Boscolo & Metzger, 2011; Goulart-Silva et al., 2015; Bueno & Peres, 2019). Therefore, the information above corroborated the hypothesis that fragmentation in the TRB occurred first in the southern portion of the basin (Cerrado biome) and, for this reason, the IS and RE metrics varied very little in the period from 1985 to 2018 (see Morton et al., 2006; Zalles et al., 2019 and Picoli et al., 2020).

However, today it is no longer a problem to analyze spatio-temporal fragmentation with the number of metric functions developed to assess the changes that occur with the remnants of the NVC (Wang et al., 2014 and Cushman & Mcgarigal, 2019). Therefore, the isolation and the edge of the fragments continue to be a problem in measuring these two variables. The current issue boils down to knowing how to choose which metric to apply among many available and their efficiency in explaining the problem in the field (Kupfer, 2012). Another issue is identifying and showing the differences in fragmentation patterns that exist depending on the studied period, biome, phytophysiognomy, and chosen metrics (Uuemaa et al., 2009 Sinha et al., 2016).

Many studies in the last 20 years have sought to show the problems related to the existing redundancy between landscape metrics, such as those that show the differences between abundance and reduction of remaining habitats over time. Unfortunately, a dozen metrics are based on this same assumption, creating confusion between the results obtained (Uuemaa et al., 2009; Kupfer, 2012).

Most metrics were developed to characterize the changes suffered in the spatial geometry of the matrix fragments and did not explain differences found between fragmentation patterns of the remaining habitats. Identifying fragmentation patterns and specific metrics remains a limitation in studies on the ecology of fragmented forests (Colson et al., 2011; Fan & Myint, 2014; Ndao et al., 2021).

4. Conclusion

The conclusions are listed below based on the results of the six metrics analyzed and on the two hypotheses raised about the fragmentation studied from 1985 to 2018 at TRB.

4.1 About landscape metrics on TRB

(1) NP vs. PS – The relationship between the metrics of the number of patches (NP) versus the size of patches (PS) showed that as the fragmentation advanced in the landscape, the number of patches grew exponentially while their areas decreased logarithmically in the landscape agricultural matrix, indicating that for 20 years the locations of remaining forests and savannas reduced to half of their original sizes on TRB;

(2) PS – The patch size (PS) metric showed that at the beginning of fragmentation, the patches were few, their areas large, and over time, they quickly lost areas within the matrix, showing two distinct periods in the fragmentation dynamics:

a) Size of the patches of forests in the Northern portion on TRB

Period I – Period I – 1985 to 2005 (20 years) was more intense and more prolonged with a class of large forest patches close together, almost forming a single block > 10^7 ha. And the second class of more minor and dispersed patches in the matrix ≥ $10^2 \geq 10^5$ ha.

Period II – 2005 to 2018 (13 years) milder and shorter with a class of forest patches smaller than the second class described above and more dispersed in the matrix ≥ $10 \leq 10^5$ ha.

b) Size of the patches of savannas in the Southern portion of TRB

Period I – 1985 to 2005 more intense and more prolonged with a class of large patches of savannas close together ≥ 10^6 ha. The second class of smaller, dispersed patches ≥ $10 \geq 10^6$ ha.

Period II – 2005 to 2018 milder and shorter with a dominant class of small patches of savannas dispersed in the matrix ≤ $10 \leq 10^5$ ha;

(3) ED – Our collected data showed the edge effect in both portions of the TRB analyzed. However, in the southern part of the basin, the patches generally had a higher percentage of edge.

a) Edge effect on the northern portion of TRB:

Period I – 1985 to 2005 was more intense and more extended, when the NVC = 75 and 100%, most forest patches had a maximum of 5% of edge, and a few varied from 5 to 15%.

Period II – 2005 to 2018 was milder and shorter. When the NVC was 50, and 75%, the edge effect in the forest patches increased to 10 to 15% in the matrix.

b) Edge effect on the southern portion of TRB:

Period I – 1985 to 2005 was more intense and more prolonged. While NVC = 75 and 100% intact, the edge percentage in most savanna patches was below 10%.

Period II – 2005 to 2018 milder and shorter, as the NVC was below 25 and 50%, the edge effect increased in the remaining savannas to 10 and 20%;

(4) IS – The isolation metric in the three classes studied showed more intense fragmentation dynamics in the northern portion. In contrast, in the southern part of the basin, the isolation of the remnants was more discreet and more difficult to be evaluated and separated into distinct periods of fragmentation.

a) Isolation of forest fragments in the Northern portion of TRB:

Period I – 1985 to 2005, it was possible to observe in the lowest isolation class from 10 to 100 m that the forest fragments reduced by 28%, showing the increase in isolation due to loss of area of the remnants in the matrix. On the other hand, in the second class of 100 to 1000 m, isolation increased to 31% in forest fragments in 2005, while in the third-largest isolation class from 1000 to 10,000 m, it hardly changed. It was only 2.8% in this period.

Period II - 2005 to 2018 showed minimal variability between the three isolation classes of forest fragments in the northern portion of the TRB. The period characterized the dynamics advanced very little in the basin, and this is probably related to the intensification of government programs for environmental enforcement or the natural regeneration of NVC.

b) Isolation of savanna fragments in the southern portion on TRB:

In the south amount of TRB, due to the minor variation in the isolation of the savanna fragments, we did not identify Periods I and II in the fragmentation dynamics from 1985 to 2018. This evidence suggested that in the southern portion of the basin (Cerrado biome), the occupation process began in some period before 1985, the beginning of the study.

The most extensive variation recorded in 20 years (1985-2005) was 11% in the second insulation class from 100 to 1000 m, then it dropped to 3.5% in 2018. The other two insulation classes analyzed from 10 to 100 and 1000 to 10,000 meters showed less than 5% variation from 1985 to 2018.

(5) IN – In the northern portion of TRB, the interiority metric of forest fragments showed two periods, a more intense and more prolonged one lasting 20 years from 1985 to 2005 and a milder and shorter 13-year period from 2005 to 2018.

In 1985 most of the forest fragments were between 10^3 and 10^4 m, and as NVC lost forest, the interiority decreased, increasing the presence of fragments by 10^2 and 10^4 meters in 2000. In 2005, when NVC was below 50%, we observed an increase in the number of forest fragments with 10^2 m of the interior, characterizing a more significant edge effect and loss of biodiversity among the remnants of the NVC in the northern portion of the basin.

In the southern portion of the TRB, the interiority metric of the savanna patches did not identify two periods in the fragmentation dynamics study, once again showing evidence of a process of occupation of the southern portion of the basin (Cerrado biome) before 1985. Examining the interiority in 1985, we observed the presence of many patches $<10^2$ m of interiority in the remaining savannas, characterizing high fragmentation of the landscape with many small patches in the landscape in the eight periods studied.

Biodiversity loss was high in the TRB Cerrado biome, with a high concentration of irregular and small patches in the southern portion. Today these remnants play an essential role in the connectivity of the landscape, functioning as Stepping-Stones between the matrix patches and the source areas around the fragmented forest in the transition of Cerrado – Amazon biomes.

(6) RE – The percentage of remnants (forests and savannas together) between 1985 and 2018 was significant in the northern and southern portions of the basin. With 38% loss of the remaining habitats in the Northern part (Amazon biome) and 41% of all remaining habitats in the Southern portion (Cerrado biome) of TRB.

The recorded loss of NVC in Cerrado was worrying in the southern portion of the basin. With increasing deforestation and high landscape fragmentation, the loss of seasonal forest habitats and shrub savannas has increased the isolation of these remnants in the agricultural matrix. The present study showed that in 1985 the southern portion of the basin had already lost 60% of the NVC.

In general, the remnants of forests and savannas analyzed in TRB did not show differentiated fragmentation patterns, e.g., like Land Sparing or Land Sharing. However, in the Cerrado biome (The southern portion of the basin), there was a tendency for fragments >250 ha to be more dispersed and isolated from each other in the matrix landscape (≈Land sparing). While, in the Amazon biome (Northern portion of the basin), the remnants of NVC showed a greater tendency to cluster, with many small fragments <50 ha and closer together dispersed in the agricultural matrix (≈land sharing). However, we believe that further considerations on the subject are still premature. At the same time, we do not have more field studies to elucidate these questions related to the fragmentation patterns of the remnants of neotropical forests and savannas.

4.2 On the hypotheses raised about the fragmentation dynamics in TRB

The PCA was fundamental to show that there was a fragmentation process in the southern portion of TRB (Cerrado biome) before 1985 and to identify which metrics and years were most correlated in the thirty-three years of the study;

Cluster analysis was fundamental to show that the fragmentation dynamics in TRB were not a single event. There was a sequence of events between the years studied in the northern portion of the basin: Cluster I (1985), Cluster II (1990 - 2005), and Cluster III (2010 - 2018). In the southern portion of the basin: Cluster I (1985 – 1990); Cluster II (1995 – 2000); Cluster III (2005 – 2015), and Cluster IV (2018).

4.3 Final considerations

- The solution of using the Grass-GIS tool (7.2.2) with LS-METRICS software (1.0) in the study of the three core areas of TRB to show the spatio-temporal changes that occurred with the remaining forests and savannas of NVC, proved to be a robust set suitable for the analysis of landscape metrics, especially considering the territorial dimensions of the basin (764,183 km²), the inconvenient problems of crashes and recurrent errors common in other available geotechnologies;
- The hexagon analytical method proved to be very efficient as a sampling unit of the geospatial changes in habitats, especially in quantifying losses of TRB remnants. Therefore, we suggest also analyzing the LULCC changes in Plateau, Depression, and Plain areas of the basin, in addition to the 03 core areas studied. We believe that the expected results of fragmentation based on relief subdivision will be more significant in explaining the differences in fragmentation patterns in Cerrado and Amazon biomes;
- Studies of forest fragmentation in entire areas of watersheds continue to be an academic novelty, especially comparative studies between world and Amazon watersheds, showing the losses of NVC and the consequences of this for the conservation of tropical forests and ecosystem services. Thus, we encourage more studies to create databases and consolidated

results that can be shared in regional programs for restoration and integrated management of watersheds, land management and planning, strategic regional planning, and wildlife conservation in threatened areas.

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