Article

Space-Time Dynamics of Land Use in the Municipality of Goianésia Do Pará, Brazil

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Abstract: Hydroelectric energy generates more than 50% of all renewable electricity in the world. The Amazon is home to a large part of these ventures, promoted as a strategy of energy independence in order to reduce greenhouse gas emissions in the countries of the region. However, these hydroelectric plants lead to changes in land cover, fragmentation, degradation, and loss of tropical forests. This article analyzes the spatial pattern of alterations in the land cover of the municipality of Goianésia do Pará, one of the seven municipalities affected by the artificial lake of the Tucuruí hydroelectric plant. This case study integrates remote sensing and landscape metrics to identify, quantify, and spatialize the loss of tropical forest within the municipality by using satellite images of the TM-Landsat 5, ETM+-Landsat 7 and OLI-Landsat 8 sensors. The results show that the average deforestation rates were high in the first two periods: 1984–1988 (23,101.2 ha per year) and 1988–1999 (13,428.6 ha per year). However, this rate drastically fell in the last period because, by 2010, more than 60% of the territory was already deforested, which shows the consolidation of the municipality's deforestation process.

1. Introduction

A total of 160 countries worldwide use electric energy, provided in part by hydroelectric plants [1]. Hydroelectric energy is the world's largest renewable energy source; it generates more than 50% of all renewable electricity in the world [1]. Additionally, hydroelectric reservoirs improve agricultural productivity and enable timely supply in irrigation systems via multiple water uses [2,3]. In South America, this type of infrastructure is promoted to achieve energy independence and reduce greenhouse gas emissions when compared with thermoelectric plants. In the Amazon region, there are 100 dams in operation and 137 planned [4,5]. The high level of precipitation and the mountainous topography of the Andean Amazon make it a region with great potential for hydroelectric energy generation [6]. However, the Brazilian Amazon is relatively flat and requires large shallow reservoirs as it is prone to sedimentation and flooding of large areas which significantly change the landscape and impact ecosystem services and biodiversity [7,8].

More specifically, the installation of hydroelectric plants in the Amazon can lead to land cover changes, forest loss, degradation, and fragmentation [9,10]. These alterations are associated with population dynamics and supplementary entrepreneurship infrastructures [10,11]. Despite its ecological and socioeconomic impacts, there are 74 dams in operation in that region [2]. Even though these dams are mainly intended to generate power for cities, there is also an expectation that hydroelectricity will play an important

role in stimulating the exploitation of mineral resources and industrialization within the Amazonia, like in the case of Tucuruí dam [12].

The Tucuruí dam was built in the Brazilian Amazon, southeast of the state of Pará, to guarantee an installed capacity of 4000 MW (Megawatts) of energy from the Tucuruí hydroelectric plant to develop the electro-intensive aluminum industry in the Amazon [11,13]. The dam was built with little to no attempt at pre-project prediction and avoidance of environmental and socio-economic problems [12]. As a result, problems arose, as the construction obstructed the Tocantins River and flooded 2430 km^2 in 1984, causing disruption in the environment as well as displacement of the populations in the area [11,14]. In addition, the resettlement affected indigenous people of the area by cutting their access to the reservoir; facilitating the entrance of non-indigenous poachers; and contributing to the transmission of diseases, such as malaria [12]. Nonetheless, the dam does contribute to generate employment, thus making it attractive for people to migrate to neighboring municipalities [15]. Goianésia do Pará is one of the municipalities that has experienced a significant expansion as a result of its proximity to the dam, as it is evident with the apparition of illegal settlements [16].

Subsequently, the Araguaia-Tocantins hydrographic basin's water resources are essential for local and regional development due to the potentially irrigable large areas for agriculture, navigation, and fishing, in addition to their rich hydroelectric potential [17,18]. The exploitation of resources, agricultural activities, and the expansion of cities, among other mentioned activities, have been connected to the loss of rainforest [19].

By being the first large hydroelectric project to be completed in Amazonia Legal Brasileira (Brazil's Amazonian administrative region), the Tucuruí dam becomes an ideal case for understanding the long-term impacts of mega-dams on rainforest loss. This study aims to evaluate the space–time deforestation pattern in the municipality of Goianésia do Pará, in the periods of pre-inauguration, completion of phase I, the start of phase II of construction, total completion of the Tucuruí hydroelectric megaproject, and the current scenario of the municipality of Goianésia do Pará, referring to 1984, 1988, 1999, 2010 and 2017, respectively. This study helps to verify the environmental alterations caused by the implementation of the artificial lake of Tucuruí through the combination of remote sensing and landscape metrics for the identification, quantification, and specialization of the loss of tropical forest within the municipality.

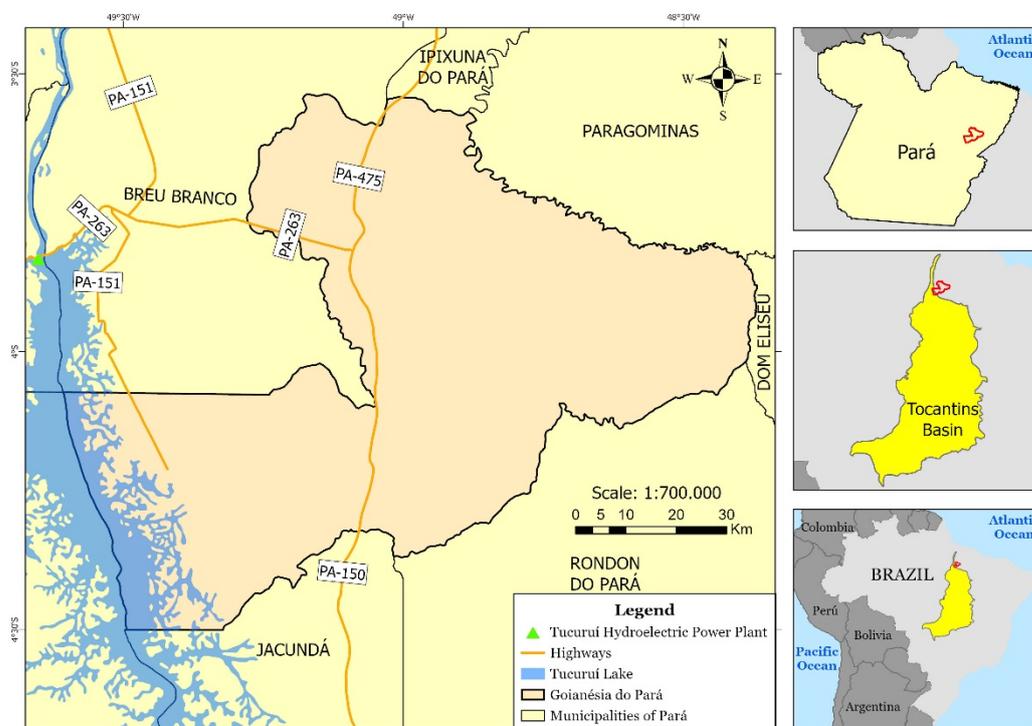## 2. Materials and Methods

2.1. Study Area

Goianésia do Pará is a Brazilian municipality in the state of Pará, delimited by latitudes 3°32′ and 4°30′ S and longitudes 48°22′ and 49°36′ W, with a territorial extension of 7009.94 km^2 [20]. According to data from the 2010 census conducted by the Brazilian Institute of Geography and Statistics, this municipality has 30,436 inhabitants [20]. Goianésia do Pará is one of the seven municipalities affected by the artificial lake of Tucuruí (Figure 1).

The Tucuruí hydroelectric plant is located in the Baixo Tocantins hydrographic subbasin [17]. It was the first of several hydroelectric plants installed in the Brazilian Amazon [21]. In 1984, the construction of its phase I was completed. In this phase, it was necessary to dam the lower Tocantins River, within the Tocantins-Araguaia River Basin, adjacent to the Amazon Basin, which flooded an area of 2430 km^2 [11,14].

The artificial lake of Tucuruí caused the displacement of the region's population; intensified insect proliferation; and caused the appearance of endemic diseases, such as malaria [22]. Trees and urban towns were flooded by the reservoir, while deforestation occurred around the lake, which produced a high degree of fragmentation of tropical forest in the region [10,23,24].

The Tucuruí hydroelectric plant had a phase II of construction that ended in 2007, reaching an installed capacity of 8370 MW of electric energy [23]. The energy produced is supplied to the Brazilian northeastern and central-western regions through high-voltage transmission lines [21]. It is important to add that the hydroelectric entrepreneurship

included the implementation of some locks to guarantee the Tocantins river's navigability. However, this infrastructure was installed in 2010, which is considered the year of total completion of the Tucuruí hydroelectric project [25].

Figure 1. Location of the study area: municipality of Goianésia do Pará.

2.2. Acquisition of Remote Sensing Data

Two scenes of adjacent images of the Landsat satellite (orbit/point: 223/63 and 224/63) were used to perform the multitemporal mapping of the municipality of Goianésia do Pará. Twelve satellite images were acquired in total, ortho-rectified with atmospherically corrected projection on UTM datum/spheroid WGS1984, with level 1 terrain precision correction (L1TP) and accuracy greater than 0.8 pixels [26]. All images correspond to the months between May and September of 1984, 1988, 1999, 2010 and 2017, obtained from the image archive of the United States Geological Survey [27].

The images from 1984, 1988, and 2010 were captured by the Thematic Mapper (TM)-Landsat 5 sensor; those from 1999 came from the Enhanced Thematic Mapper Plus (ETM+)-Landsat 7 sensor; and the images from 2017 were captured by the Operational Land Imager (OLI)-Landsat 8 sensor. Although multiple sensors were used to collect the data, the quality of the images, the spatial resolution, the geometry, and the length of the images remained consistent [26]. The large presence of clouds in the region of interest made it difficult to use a single image. For this reason, the use of complementary images was needed for both locations in 1999 and 2010. Finally, all the images were placed in a database to store the processed information, where free software, TerraAmazon [28] and PostgreSQL [29], was used.

2.3. Data Processing and Analysis of Deforestation Patterns

In order to assist with the identification of the features in the classification process, on the TerraAmazon software, the red, green and blue (RGB) color composition was prepared using the near infrared (NIR), the shortwave infrared (SWIR-1), and red (R) bands, respectively. Subsequently, the linear contrast enhancement of the images was run to improve differentiation between the relevant classes.

Next, an algorithm available at TerrAmazon software, using the linear spectral mixture model (LSMM) of the NIR, SWIR-1, and R bands of the Landsat images, was used to

select pixels that represent the soil, shadow, and vegetation components [30]. The LSMM estimated the pixel proportions of shadow, vegetation, and soil, and to enhance these components, thus facilitating the identification of deforestation [30]. Afterward, the image segmentation algorithm by region growth was executed to facilitate the discrimination of the classes. This algorithm helps to group the pixels according to the similarity threshold to define the distance in which a pixel can belong to a group and, according to the area threshold, to determine the minimum size of each pixel group [30]. For the algorithm, the similarity thresholds of 16 digital numbers and area thresholds of (~0.7 ha) were used. The segmented shade and soil fraction images were also used for the visual interpretation in the polygon-to-polygon classification [23].

A polygon-to-polygon supervised classification of the vectors resulting from the segmentation of the ground and shadow fraction images was performed at a scale of 1:30,000. They were classified according to the objects' spectral response in the RGB color composition of the NIR, SWIR-1, and R bands of the TM-Landsat 5, ETM+-Landsat 7, and OLI-Landsat 8 sensors. The matrix edition of the wrongly classified areas was then carried out by visual reclassification at a scale of 1:30,000 [24,25].

The interpretation key of the classes was based on both the Amazon Deforestation Monitoring Project [31,32] and the spectral behavior of the objects in relation to the shade and soil response of the LSMM. The selected classes were: (1) forest, i.e., forest formations that do not show any anthropic interference; (2) anthropized area, i.e., all types of interference in forest formations (agriculture, farming, deforested areas, occupation mosaics) and exposed soils related to sandbars and floodplains; (3) flooded area, i.e., that which covers the artificial lake of Tucuruí; (4) water, including the other bodies of water (rivers, ponds, and wells); (5) urban area, i.e., urban cover spots; and (6) cloud, i.e., areas covered by cloud and cloud shadow.

Finally, the landscape structure was quantified using the FRAGSTATS software [33] to determine the classes and landscape metrics. In order to analyze the spatiotemporal patterns of landscape change, some of the metrics used in similar studies were considered in order to identify and spatialize deforestation patterns [24,25,34,35]. Thus, concerning the entire landscape and mapped classes, the metrics of the number of class fragments (NP), the area of class fragments (CA), the average size of class fragments (MPS), the fragment density of classes (PD), and the fragment area (AREA) were assessed.
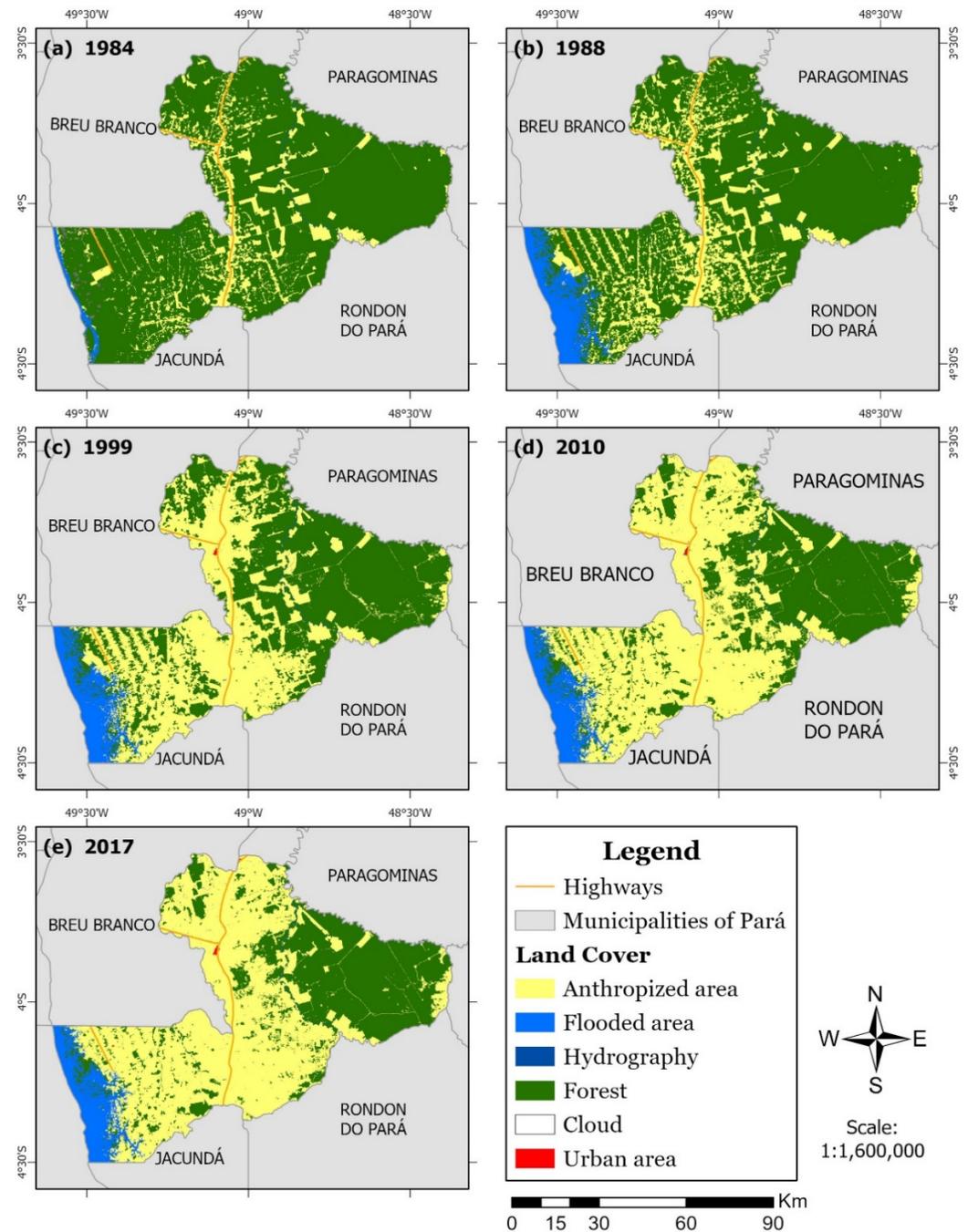
3. Results and Discussion

The digital processing of the satellite images provided the land cover maps of the municipality of Goianésia do Pará, for 1984, 1988, 1999, 2010 and 2017 (Figure 2). These maps facilitated the spatial analysis of the municipality's coverage pattern throughout the 33 years of operation of the Tucuruí hydroelectric power plant considered in this study. In the maps on Figure 2, landscape alterations are observed. The area values in hectares (ha) and the percentage occupied by each class are found in Table 1.

When quantifying the classes shown in the maps of Figure 2, it can be observed that urban and anthropized areas throughout the 33 years of analysis experienced an expansion of 4.1 times in relation to the year 1984. In this way, the urban area class went from 67 ha to 79 ha in 1988, to 267 ha in 1999, to 532 ha in 2010, and to 595 ha in 2017. Concerning the anthropized class, they went from 98,840 ha to 152,623 ha in 1988, to 300,264 ha in 1999, to 379,844 ha in 2010, and to 409,797 ha in 2017, which led to a fall in the predominance of tropical forest in the municipality (Table 1). Similar results were obtained by Terraclass Mapbiomas projects regarding urban and anthropized areas [36,37]. According to those projects, most of the anthropized area is used for cattle ranching as pasture.

This urban expansion, starting from the decade of 1980′s, is associated to the construction of the UHT Tucuruí, as well as to the program *Grande Carajás*, which was important for the execution of industrial projects, as it gave financial and fiscal incentives to projects that were considered important for the development of the area. In turn, the program demanded the construction of infrastructure which was possible though special programs,

such as the Amazon Agricultural and Agromineral Poles Program (POLAMAZONIA, by its name in Portuguese), which valued the mineral and energy potential of the region, making entrepreneurships related to them viable [16].

Figure 2. Thematic maps of land cover in the municipality of Goianésia do Pará, concerning the years 1984 (**a**), 1988 (**b**), 1999 (**c**), 2010 (**d**), and 2017 (**e**).

Table 1. Areas and relative participation of land cover classes in the municipality of Goianésia do Pará.

Classes	Area [ha]					Relative Participation [%]				
	1984	1988	1999	2010	2017	1984	1988	1999	2010	2017
Forest	593,081	500,677	352,962	273,299	241,000	84.61	71.43	50.35	38.99	34.38
Anthropized area	98,840	152,623	300,264	379,844	409,797	14.10	21.77	42.83	54.18	58.46
Flooded area	6897	45,982	45,618	45,219	47,075	0.98	6.56	6.51	6.45	6.72
Urban area	67	79	267	532	595	0.01	0.01	0.04	0.08	0.08
Hydrography	1472	1618	1867	2084	2501	0.21	0.23	0.27	0.30	0.36
Cloud	621	0	0	0	11	0.09	0.00	0.00	0.00	0.00
Total	700,979	700,979	700,979	700,979	700,979	100	100	100	100	100

The largest expansion of deforested areas in the municipality of Goianésia do Pará occurred between 1988 and 1999, which varied from 152,702 ha to 300,531 ha. In turn, the lowest expansion of deforested areas happened between 2010 and 2017, from 380,376 ha to 410,392 ha. This decrease in the last analysis period may be linked to the fact that, in 2010, more than 50% of the municipality was already covered by anthropized areas (see Table 1).

In the early years (1984 and 1988), we noticed a spatial relationship between deforestation and roads. Afterward, deforestation grows, removing almost all forest cover from the west region where the main roads (PA-150, PA-151, PA-263, and PA-275) are located. In 1984, the anthropized areas were concentrated around the PA-150, PA-263, and PA-475 highways and dispersed in the central region, from north to south of the municipality. The town of Goianésia do Pará (67 ha) was the only urban patch detected, located on the periphery of the PA-150 highway, near the PA-263 and PA-475 junction (Figures 1 and 2a). The PA-475 road connects the town of Goianésia do Pará with that of Tailândia, the main town in the municipality of the same name, located north of the municipality of Goianésia do Pará. Furthermore, the PA-263 highway connects the town of Goianésia do Pará with that of Breu Branco, the main town in the municipality that bears the same name in the northwest of the municipality of Goianésia do Pará (Figure 1). This deforestation pattern associated with roads is recurrent in Amazon, linking deforestation with infrastructure projects, agriculture, and land grabbing, among others [38–41].

By 1988, the town of Goianésia do Pará (71 ha) continues to be the only urban patch detected (Figure 2b). The anthropized areas continue to be concentrated around PA-150, PA-263, and PA-475 highways, and the central region, from north to south of the municipality; however, the greatest presence of anthropized areas occurs west of the municipality, specifically in the area located between Lake Tucuruí and the PA-150 highway. This territorial distribution may be linked to access better water sources for the extension of irrigable areas due to water availability from the artificial lake of Tucuruí. It must be noted that, for this scenario, Lake Tucuruí flooded 2551.3 ha of anthropized areas and 35,959 ha of tropical forest.

For the 1999 scenario, a new patch was identified on the periphery of the PA-475 Highway, north of the municipality. However, the town of Goianésia do Pará is the largest urban patch (236 ha). The anthropized areas are completely scattered around the PA-150, PA-263, and PA-475 highways and west of the municipality, the area limited by the PA-150 highway and Lake Tucuruí. There is a reduction in the size of the tropical forest segments in all these regions until their disappearance, especially in the central region, from north to south of the municipality (Figure 2c).

The expansion of anthropized areas, as well as the continuous urbanization as a result of the industrial expansion on the area during the time period of 1991–2010, had a positive effect on the socioeconomic development of the region. This is evident when looking at census data where it is evident that the human development index (HDI) in the municipality of Goianésia do Pará experienced a steady increase from 0.235 in 1991 to 0.56 in 2010 [42]. The increase in the HDI of the area corresponds with the expansion of

the municipality's urban areas. Nonetheless, the 0.56 score is far from ideal in a scale from 0 to 1, where 1 represents the highest HDI score.

Concerning the years 2010 and 2017, new urban patches were identified. The town of Goianésia do Pará corresponds to the largest urban patch with 438 ha in 2010 and 454 ha in 2017. Regarding the anthropized areas, they are much more dispersed around the PA-150, PA-263, and PA-475 highways, and the west and northeast of the municipality (Figure 2d,e). In these two scenarios, the municipality of Goianésia do Pará already had few areas of tropical forest, as confirmed in Table 2 which shows the number of forest areas and their land cover rate in the municipality.

Table 2. Number of fragments and land cover rate of forest in 1984, 1988, 1999, 2010, and 2017.

Size of Fragments [ha]	Number of Fragments					Relative Land Cover				
	1984	1988	1999	2010	2017	1984	1988	1999	2010	2017
<1	86	144	78	442	172	0.00	0.01	0.00	0.02	0.01
1–5	92	216	210	309	471	0.04	0.08	0.09	0.12	0.18
5–10,000	118	317	586	760	911	2.41	7.29	14.34	15.05	12.54
>10,000	3	4	3	1	1	82.16	64.04	35.93	23.80	21.65
Total	299	681	877	1512	1555	84.61	71.43	50.35	38.99	34.38

According to the data in Table 2, in the municipality of Goianésia do Pará, by 1984 and 1999, three large forest fragments (>10,000 ha) were identified, representing 82.16% and 35.93% of the municipality's landscape, respectively. By 1988, the total number of large fragments was four, covering 64.04% of the territory. In the scenarios of the years 2010 and 2017, only one large forest fragment was identified, representing 23.80% and 21.65% of the municipality's landscape, respectively. This result confirms the fall of forest cover in the study area, which caused fragmentation and loss of tropical forest segments. The most fragmented landscapes contain smaller forest segments of average size since the number of fragments and the entire tropical forest area are related [33]. This fact is considered a good indicator of the fragmentation degree. This relationship is complemented when analyzing the average size of a forest fragment and its densities as a whole [43]. The results of Table 3 show the fragmentation process in the municipality of Goianésia do Pará, throughout the 33 years of analysis, evidenced by a reduction in the average size (MPS) and an increase in the density (PD) of the forest fragments over time. This happens because fragmentation increases isolation and leads to greater exposure to human land uses and exploitation along the fragment edges, thus initiating long-term changes to the structure and function of the remaining fragments [44,45].

Table 3. Number (NP) density (PD) and average size of forest fragments (MPS) in the years 1984, 1988, 1999, 2010, and 2017.

Year	NP [Unit]	PD [frag./100 ha]	MPS [ha]
1984	299	0.04	1983.55
1988	681	0.10	735.21
1999	877	0.13	402.47
2010	1512	0.22	180.75
2017	1555	0.22	154.98

The municipality of Goianésia do Pará presented MPS metrics of forest fragments of 1984 ha in 1984, 735 ha in 1988, 402 ha in 1999, 181 ha in 2010, and 156 ha in 2017. Meanwhile, the PD values of forest fragments were 0.04 frag./100 ha in 1984, 0.10 frag./100 ha in 1988, 0.13 frag./100 ha in 1999, 0.22 frag./100 ha in 2010, and 2 frag./100 ha in 2017. These results also coincide with the progressive variation in the number of spots in the landscape (NP), which was initially 299 segments in 1984 and turned to 681, 877, 1512 and 1555 segments in the years 1988, 1999, 2010 and 2017, respectively. This increase confirms the progressive

fragmentation and forest loss within the municipality, an effect that was already perceived in the temporal maps in Figure 2.

The dynamics of the landscape resulting from the process of implementation of the Tucuruí hydroelectric dam indicated that the segments of forest areas increased in number but decreased in size, which clearly illustrates its fragmentation. The pattern initially observed for altered areas in 1984 reflects the herringbone shape observed on the Trans-Amazonian highway [46]. However, from 1988 to 2010, the pattern also acquired the diffuse behavior characteristic of small rural properties (from pioneer to established) [47]. These properties were absorbed by consolidated rural ones so that, in 2010, the main alteration segment was continuous and contained several isolated forest segments, with extensive continuity gaps. This behavior evidences a process of consolidation for the region and complex reversibility for the recovery of the affected ecological systems, as reflected through the entire Brazilian Amazon [45].

This pattern is an example of the diverse forms of forest alterations that reveal the dynamics of the Brazilian Amazon ecosystems. In this region, the increase in forest fragmentation results from the progressive forest division into small and isolated segments of various sizes and shapes. This phenomenon results in a diversity of negative impacts, such as altering population dynamics and size, which may modify the overall ecosystem function and forest condition [48,49], since the effects of fragment size and habitat loss act together. In addition, the fragmentation of tropical forests has proven to have a negative effect on biodiversity, given that the reduced area decreases animal residency and promotes isolation, thus affecting the ability of species to persists. Furthermore, fragmentation has a degrading effect on a disparate set of core ecosystem functions, including the reduced carbon and nitrogen retention, which affects the carbon cycle, productivity, and pollination, among others, creating global changes [44,45,50–53]. This emphasizes the importance of tropical forest conservation policies that include fragmentation metrics [44].

4. Conclusions

The multitemporal use of land cover maps from Landsat images allows for the assessment of forest fragmentation and its dynamics in forest ecosystems. This study established a baseline of forest fragmentation in the municipality of Goianésia do Pará, through the characterization of fragmentation of the Amazon rainforest, among the different stages of construction and the current scenario of the Tucuruí hydroelectric dam. It was confirmed that the deforestation rates were 23,101 ha/year between 1984 and 1988, 13,429 ha/year between 1988 and 1999, 7242 ha/year between 1999 and 2010, and 4614 ha/year between 2010 and 2017. It is important to point out that, by 2010, more than 60% of the territory was already deforested. By examining the values of fragmentation metrics, it was possible to confirm the temporal evolution of forest fragmentation, especially in the regions disturbed by the PA-150, PA-263, and PA-475 highways, which facilitated the access to forests and the conversion of the same into agricultural extension and grazing areas.

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References

1. International Renewable Energy Agency. *Renewable Capacity Statistics*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.
2. Kumar Sharma, A.; Thakur, N.S. Energy Situation, Current Status and Resource Potential of Run of the River (RoR) Large Hydro Power Projects in Jammu and Kashmir: India. *Renew. Sustain. Energy Rev.* **2017**, *78*, 233–251. [CrossRef]
3. McDonald, R.I.; Olden, J.D.; Opperman, J.J.; Miller, W.M.; Fargione, J.; Revenga, C.; Higgins, J.V.; Powell, J. Energy, Water and Fish: Biodiversity Impacts of Energy-Sector Water Demand in the United States Depend on Efficiency and Policy Measures. *PLoS ONE* **2012**, *7*, e50219. [CrossRef]
4. Tundisi, J.G.; Goldemberg, J.; Matsumura-Tundisi, T.; Saraiva, A.C.F. How Many More Dams in the Amazon? *Energy Policy* **2014**, *74*, 703–708. [CrossRef]
5. International Energy Agency Key World Energy Statistics. 2020. Available online: https://www.iea.org/reports/key-world-energy-statistics-2020 (accessed on 20 September 2020).
6. McClain, M.E.; Naiman, R.J. Andean Influences on the Biogeochemistry and Ecology of the Amazon River. *BioScience* **2008**, *58*, 325–338. [CrossRef]
7. Barrow, C. The Impact of Hydroelectric Development on the Amazonian Environment: With Particular Reference to the Tucurui Project. *J. Biogeogr.* **1988**, *15*, 67–78. [CrossRef]
8. Soito, J.L.D.S.; Freitas, M.A.V. Amazon and the Expansion of Hydropower in Brazil: Vulnerability, Impacts and Possibilities for Adaptation to Global Climate Change. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3165–3177. [CrossRef]
9. Chen, G.; Powers, R.P.; de Carvalho, L.M.T.; Mora, B. Spatiotemporal Patterns of Tropical Deforestation and Forest Degradation in Response to the Operation of the Tucuruí Hydroelectric Dam in the Amazon Basin. *Appl. Geogr.* **2015**, *63*, 1–8. [CrossRef]
10. Velastegui-Montoya, A.; de Lima, A.; Adami, M. Multitemporal Analysis of Deforestation in Response to the Construction of the Tucuruí Dam. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 583. [CrossRef]
11. Fearnside, P.M. Social Impacts of Brazil's Tucuruí Dam. *Environ. Manag.* **1999**, *24*, 483–495. [CrossRef]
12. Barrow, C.J. The Environmental Impacts of the Tucuri Dam on the Middle and Lower Tocantins River Basin, Brazil. *Regul. Rivers Res. Manag.* **1987**, *1*, 49–60. [CrossRef]
13. Fearnside, P.M. Environmental and Social Impacts of Hydroelectric Dams in Brazilian Amazonia: Implications for the Aluminum Industry. *World Dev.* **2016**, *77*, 48–65. [CrossRef]
14. La Rovere, E.L.; Mendes, F.E. Tucuruí Hydropower Complex, Brazil; Cape Town. 2000. Available online: https://www.internationalrivers.org/sites/default/files/attached-files/csbrmain.pdf (accessed on 20 June 2021).
15. Velastegui-Montoya, A.; de Lima, A.; Herrera-Matamoros, V. What Is the Socioeconomic Impact of the Tucuruí Dam on Its Surrounding Municipalities? *Sustainability* **2022**, *14*, 1630. [CrossRef]
16. Prefeitura de Municipal de Goianésia História de Goianésia Do Pará. Available online: https://goianesia.pa.gov.br/o-municipio/historia/ (accessed on 2 October 2021).
17. Agência Nacional de Águas. *Plano Estratégico de Recursos Hídricos Da Bacia Hidrográfica Dos Rios Tocantins e Araguaia: Relatório Síntese*; ANA-Agência Nacional De Águas: Brasília, Brazil, 2009.
18. Velástegui, A.D.M.; de Lima, A.M.M.; da Rocha, E.J.P.; Pereira Filho, A.J. Water Use Conflicts in Low Tocantins River: Analysis of Trends. *Bol. De Geogr.* **2018**, *36*, 14–30. [CrossRef]
19. Tritsch, I.; le Tourneau, F.M. Population Densities and Deforestation in the Brazilian Amazon: New Insights on the Current Human Settlement Patterns. *Appl. Geogr.* **2016**, *76*, 163–172. [CrossRef]
20. Instituto Brasileiro de Geografia e Estatística Panorama Goianésia Do Pará. Available online: https://cidades.ibge.gov.br/brasil/pa/goianesia-do-para/panorama (accessed on 20 September 2020).
21. Manyari, W.V.; de Carvalho, O.A. Environmental Considerations in Energy Planning for the Amazon Region: Downstream Effects of Dams. *Energy Policy* **2007**, *35*, 6526–6534. [CrossRef]
22. Fearnside, P.M. Environmental Impacts of Brazil's Tucuruí Dam: Unlearned Lessons for Hydroelectric Development in Amazonia. *Environ. Manag.* **2001**, *27*, 377–396. [CrossRef]
23. Fearnside, P.M. Greenhouse Gas Emissions from a Hydroelectric Reservoir (Brazil's Tucuruí Dam) and the Energy Policy Implications. *Water Air Soil Pollut.* **2002**, *133*, 69–96. [CrossRef]
24. Velástegui, A.D.M.; de Lima, A.M.M.; Adami, M. Mapping and Temporary Analysis of the Landscape in the Tucuruí-Pa Reservoir Surroundings. *Anu. Do Inst. De Geocienc.* **2018**, *41*, 553–567. [CrossRef]
25. Velástegui, A.D.M.; de Lima, A.M.M.; Adami, M. Analysis of the Land Cover Around a Hydroelectric Power Plant in the Brazilian Amazon. *Anu. Do Inst. De Geocienc.* **2019**, *42*, 74–86. [CrossRef]

26. Gutman, G.; Huang, C.; Chander, G.; Noojipady, P.; Masek, J.G. Assessment of the NASA–USGS Global Land Survey (GLS) Datasets. *Remote Sens. Environ.* **2013**, *134*, 249–265. [CrossRef]

27. United States Geological Survey. Earth Explorer. Available online: https://earthexplorer.usgs.gov/ (accessed on 26 January 2022).

28. Instituto Nacional de Pesquisas Espaciais. *TerraAmazon*; INPE: São Jose dos Campos, Brazil, 2016; Available online: http://www.terraamazon.dpi.inpe.br/ (accessed on 20 January 2020).

29. University of California. *PostgreSQL*; UC: Berkeley, CA, USA, 2012; Available online: https://www.postgresql.org/ (accessed on 20 January 2020).

30. Shimabukuro, Y.E.; Duarte, V.; Arai, E.; Freitas, R.M.; Lima, A.; Valeriano, D.M.; Brown, I.F.; Maldonado, M.L.R. Fraction Images Derived from Terra Modis Data for Mapping Burnt Areas in Brazilian Amazonia. *Int. J. Remote Sens.* **2009**, *30*, 1537–1546. [CrossRef]

31. Camara, G.; Valeriano, D.; Vianei, J. *Metodologia Para o Cálculo Da Taxa Anual de Desmatamento Na Amazônia Legal*; INPE: São Jose dos Campos, Brazil, 2013; Available online: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes/pdfs/metodologia_taxaprodes-1.pdf (accessed on 22 June 2021).

32. Souza, A.; Miguel Vieira Monteiro, A.; Daleles Rennó, C.; Aparecido Almeida, C.; de Morisson Valeriano, D.; Morelli, F.; Vinhas, L.; Eduardo Maurano, L.P.; Adami, M.; Isabel Sobral Escada, M.; et al. *Metodologia Utilizada Nos Projetos PRODES e DETER*; INPE: São Jose dos Campos, Brazil, 2019; Available online: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes (accessed on 22 June 2021).

33. McGarigal, K.; Marks, B.J. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 1995. Available online: https://www.fs.usda.gov/treesearch/pubs/3064 (accessed on 20 June 2020).

34. Vidolin, G.P.; Biondi, D.; Wandembruck, A. Análise Da Estrutura Da Paisagem de Um Remanescente de Floresta Com Araucária, Paraná, Brasil. *Rev. Árvore* **2011**, *35*, 515–525. [CrossRef]

35. Llerena-Montoya, S.; Velastegui-Montoya, A.; Zhirzhan-Azanza, B.; Herrera-Matamoros, V.; Adami, M.; de Lima, A.; Moscoso-Silva, F.; Encalada, L. Multitemporal Analysis of Land Use and Land Cover within an Oil Block in the Ecuadorian Amazon | Enhanced Reader. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 191. [CrossRef]

36. De Almeida, C.A.; Coutinho, A.C.; Esquerdo, J.C.D.M.; Adami, M.; Venturieri, A.; Diniz, C.G.; Dessay, N.; Durieux, L.; Gomes, A.R. High Spatial Resolution Land Use and Land Cover Mapping of the Brazilian Legal Amazon in 2008 Using Landsat-5/TM and MODIS Data. *Acta Amaz.* **2016**, *46*, 291–302. [CrossRef]

37. MapBiomas Brasil. Coleção V6.0 Da Série Anual de Mapas de Uso e Cobertura Da Terra Do Brasil. Available online: https://plataforma.brasil.mapbiomas.org/?activeBaseMap=8&layersOpacity=70&activeModule=coverage&activeModuleContent=coverage%3Acoverage_main&activeYear=2020&mapPosition=-15.127303%2C-51.419045%2C4&timelineLimitsRange=1985%2C2020&baseParams[territoryType]= (accessed on 2 November 2021).

38. Hosonuma, N.; Herold, M.; de Sy, V.; de Fries, R.S.; Brockhaus, M.; Verchot, L.; Angelsen, A.; Romijn, E. An Assessment of Deforestation and Forest Degradation Drivers in Developing Countries. *Environ. Res. Lett.* **2012**, *7*, 044009. [CrossRef]

39. Laurance, W.F.; Albernaz, A.K.M.; Schroth, G.; Fearnside, P.M.; Bergen, S.; Venticinque, E.M.; da Costa, C. Predictors of Deforestation in the Brazilian Amazon. *J. Biogeogr.* **2002**, *29*, 737–748. [CrossRef]

40. Pfaff, A.; Robalino, J.; Walker, R.; Aldrich, S.; Caldas, M.; Reis, E.; Perz, S.; Bohrer, C.; Arima, E.; Laurance, W.; et al. Road Investments, Spatial Spillovers, and Deforestation in the Brazilian Amazon. *J. Reg. Sci.* **2007**, *47*, 109–123. [CrossRef]

41. Souza, A.; Pontes, N.; Adami, M.; Narvaes, S. A Contribuição Das Estradas e o Padrão de Desflorestamento e Degradação Da Cobertura Florestal No Sudoeste Paraense. *Rev. Bras. De Cartogr.* **2017**, *69*, 1711–1724.

42. Instituto Brasileiro de Geografia e Estatística. Cidades e Estados Cidades e Estados: Goianésia Do Pará. Available online: https://www.ibge.gov.br/cidades-e-estados/pa/goianesia-do-para.html (accessed on 2 November 2021).

43. Valente, R.d.O.A. Análise Da Estrutura Da Paisagem Na Bacia Do Rio Corumbataí, SP. Master's Thesis, Escola Superior de Agricultura Luiz de Queiroz, Piracicaba, Brazil, 2004. [CrossRef]

44. Hansen, M.C.; Wang, L.; Song, X.-P.; Tyukavina, A.; Turubanova, S.; Potapov, P.V.; Stehman, S.V. The Fate of Tropical Forest Fragments. *Sci. Adv.* **2020**, *6*, 8574–8585. [CrossRef]

45. Haddad, N.M.; Brudvig, L.A.; Clobert, J.; Davies, K.F.; Gonzalez, A.; Holt, R.D.; Lovejoy, T.E.; Sexton, J.O.; Austin, M.P.; Collins, C.D.; et al. Habitat Fragmentation and Its Lasting Impact on Earth's Ecosystems. *Sci. Adv.* **2015**, *1*, e1500052. [CrossRef]

46. Batistella, M.; Robeson, S.; Moran, E.F. Settlement Design, Forest Fragmentation, and Landscape Change in Rondônia, Amazônia. *Photogramm. Eng. Remote Sens.* **2003**, *69*, 805–812. [CrossRef]

47. Neiva Sampaio, S.M.; Venturieri, A.; Rodrigues da Silva, B.N.; Teixeira Silva, L.G.; Oyama Homma, A.K.; Carvalho, R.d.A. *Dinâmica Da Cobertura Vegetal e Uso Da Terra No Sudeste Paraense: O Caso Do Projeto de Assentamento São Francisco*; Embrapa: Brasília, Brazil, 2003.

48. Wickham, J.D.; Riitters, K.H.; Wade, T.G.; Homer, C. Temporal Change in Fragmentation of Continental US Forests. *Landsc. Ecol.* **2008**, *23*, 892–898. [CrossRef]

49. Laurance, W.F.; Vasconcelos, H.L.; Lovejoy, T.E. Forest Loss and Fragmentation in the Amazon: Implications for Wildlife Conservation. *Oryx* **2000**, *34*, 39–45. [CrossRef]

50. Brinck, K.; Fischer, R.; Groeneveld, J.; Lehmann, S.; Dantas De Paula, M.; Pütz, S.; Sexton, J.O.; Song, D.; Huth, A. High Resolution Analysis of Tropical Forest Fragmentation and Its Impact on the Global Carbon Cycle. *Nat. Commun.* **2017**, *8*, 14855. [CrossRef]

51. Chaplin-Kramer, R.; Ramler, I.; Sharp, R.; Haddad, N.M.; Gerber, J.S.; West, P.C.; Mandle, L.; Engstrom, P.; Baccini, A.; Sim, S.; et al. Degradation in Carbon Stocks near Tropical Forest Edges. *Nat. Commun.* **2015**, *6*, 10158. [CrossRef] [PubMed]
52. Pütz, S.; Groeneveld, J.; Henle, K.; Knogge, C.; Martensen, A.C.; Metz, M.; Metzger, J.P.; Ribeiro, M.C.; de Paula, M.D.; Huth, A. Long-Term Carbon Loss in Fragmented Neotropical Forests. *Nat. Commun.* **2014**, *5*, 6037. [CrossRef] [PubMed]
53. Laurance, W.F.; Camargo, J.L.C.; Luizão, R.C.C.; Laurance, S.G.; Pimm, S.L.; Bruna, E.M.; Stouffer, P.C.; Bruce Williamson, G.; Benítez-Malvido, J.; Vasconcelos, H.L.; et al. The Fate of Amazonian Forest Fragments: A 32-Year Investigation. *Biol. Conserv.* **2011**, *144*, 56–67. [CrossRef]