Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 34, n. 2, e71255, p. 1-29, Apr./June 2024 • https://doi.org/10.5902/1980509871255
Submitted: 5th/08/2022 • Approved: 23rd/08/2023 • Published: 7th/06/2024

Articles

Spatio-temporal assessment of selective logging in Pará state, Brazil

Avaliação espaço-temporal da exploração seletiva de madeiras no estado do Pará, Brasil

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ABSTRACT

Detecting and monitoring selectively logged forests can improve the scientific knowledge related to the effects of forest degradation in tropical forests and support the environmental law enforcement of controlling and monitoring those forest activities in the Amazon region. In this study, we analyzed the spatial and temporal dynamics of forests disturbed by selective logging in Pará state, Brazil, using a time series (1992 to 2018) of Landsat images and remote sensing techniques. Forests affected by those activities were mapped using visual interpretation and semi-automatic remote sensing techniques. The results of this study showed that approximately 20% of the forests selectively logged for timber purposes were deforested in the studied area and period. We observed that the total area of forests altered by selective logging exceeded the deforested area in some years of this analysis. There was an increase in selectively logged forests within protected areas (Conservation Units and Indigenous Lands) between 1992 and 2018. Most of the selectively logged forests were spatially located in the region known as the arc of deforestation in the Brazilian Amazon. More recently, forests impacted by those activities have been detected in the new deforestation frontiers in western Pará.

Keywords: Amazon; Tropical Forest; Remote sensing

RESUMO

A detecção e monitoramento de florestas exploradas seletivamente pode melhorar o conhecimento científico relacionado aos efeitos da degradação florestal em florestas tropicais e apoiar a aplicação da lei ambiental de controle e monitoramento dessas atividades florestais na região Amazônica. Neste estudo, foram analisadas a dinâmica espacial e temporal das florestas perturbadas pela exploração seletiva de madeiras no estado do Pará, utilizando uma série temporal (1992 a 2018) de imagens Landsat e técnicas de sensoriamento remoto. Foram mapeadas as florestas afetadas por atividades de exploração seletiva aplicando interpretação visual e técnicas de sensoriamento remoto semiautomática. Os resultados deste estudo mostraram que aproximadamente 20% das florestas exploradas seletivamente para fins madeireiros foram desmatadas na área e período de estudo. Observamos que a área total de florestas alterada pela exploração seletiva de madeiras superou a área desmatada em alguns anos desta análise. Houve aumento de florestas exploradas seletivamente dentro de áreas protegidas (Unidades de Conservação e Terras Indígenas) entre 1992 e 2018. A maioria das florestas exploradas seletivamente estava localizada na região conhecida como arco do desmatamento na Amazônia brasileira. Nos anos mais recentes desta análise, as florestas impactadas por atividades madeireiras foram detectadas nas novas fronteiras de desmatamento localizadas na região oeste do estado do Pará.

Palavras-chave: Amazônia; Floresta Tropical; Sensoriamento remoto

1 INTRODUCTION

Selective logging consists of pinpointing and removing trees with the highest commercial value (Asner *et al*., 2005). Initially, this type of logging preferred one or two species, such as mahogany - Swietenia macrophylla King (Veríssimo *et al*., 1995) and Ipê (Tabebuia impetiginosa and T. serratifolia) (Schulze *et al*., 2008). Nowadays, selective logging involves cutting down 80 or more native Amazon species (Brancalion *et al*., 2018).

Contrasting with tropical forest deforestation, which is easily detected by satellites due to the clear-cutting of trees, mapping and identifying areas with selective logging is more complex, as it involves activities such as felling trees, opening roads, dragging trails, and building woodyards (Pinheiro *et al*., 2016). These activities increase forest degradation (Verissimo *et al*., 1992) and consequently reduce their capacity to provide goods and services (FAO, 2011).

Although selective logging does not include cutting down all trees in a forest, it can severely damage trees during logging operations (Nepstad *et al*., 1999; Verissimo *et al*., 1992). There are numerous consequences and impacts of selective logging, such as changes in the biophysical properties of the forest (Koltunov *et al*., 2009), changes in the structure, composition, and functioning of the forest (Longo *et al*., 2020), biomass loss due to the fall of extracted trees (Gatti *et al*., 2015), and increased forest susceptibility to fire (Uhl *et al*., 1997; Cochrane, 1998). Selective logging also contributes to carbon emissions and carbon stock reductions in tropical regions (Miller *et al*., 2011; Goodman *et al*., 2019; Umunay *et al*., 2019; Longo *et al*., 2020). Despite this, the impacts of selective logging can vary according to the cutting cycle and logging intensity, which consequently affect the forest disturbance level. In this sense, illegal logging, which does not adopt forest management techniques, causes much more impact on the forest (DeArmond *et al*., 2023).

Given the importance of different forest degradation levels as a source of carbon emissions, research to pinpoint and map selectively logged areas has become a vital component in the international context since reducing carbon emissions is one of the five strategies of the projects for Reducing Emissions from Deforestation and Forest Degradation, including conservation activities, sustainable forest management and increasing forest carbon stocks (REDD+) (UNFCCC, 2007). Recently, the state of Pará launched the Amazônia Agora State Plan (PEAA), which devotes efforts to combating deforestation, reducing greenhouse gases, and implementing a new model of economic, social, environmental, and institutional reproduction on a sustainable basis (SEMAS, 2021).

In this context, geotechnologies such as remote sensing stand out as a technically and economically viable way of systematically monitoring and identifying selective logging on broad spatial scales (Hethcoat *et al*., 2019). Several authors have used data from optical sensors to monitor selective logging in the Amazon (Watrin; Rocha, 1992; Stone; Lefebvre, 1998; Nepstad *et al*., 1999; Souza; Barreto, 2000; Asner *et al*., 2005; Matricardi *et al*., 2007, 2010, 2013, 2020; Costa *et al*., 2019; Moretti *et al*., 2020).

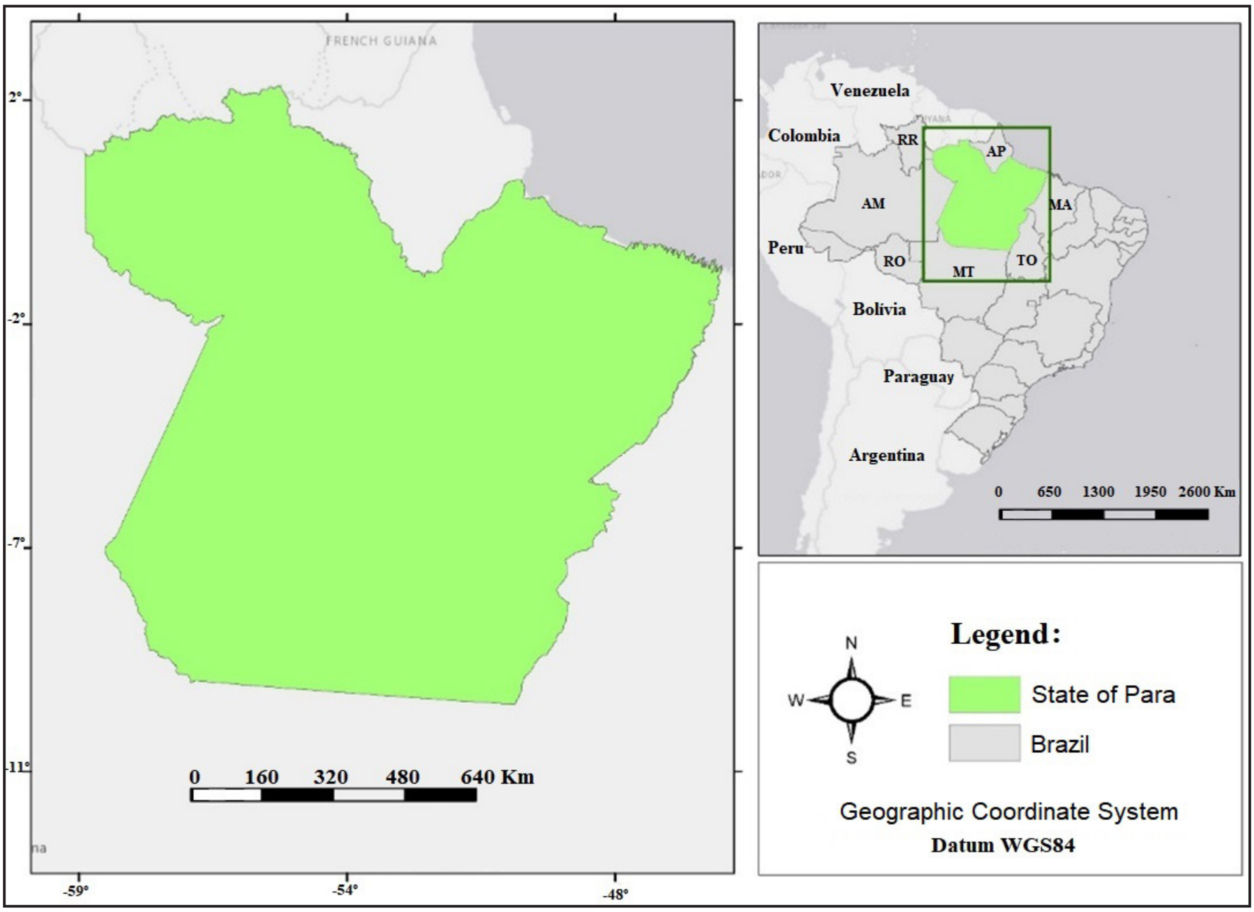
This study used remote sensing data and techniques to analyze the spatio-temporal dynamics of selectively logged forests in Pará state from 1992 to 2018. In addition, we sought to verify possible subsequent land uses in exploiting native forests in the study area and period.

2 MATERIALS AND METHODS

2.1 Location and characterization of the study area

The study area comprises the entire territory of Pará (Figure 1), located in the northern region of Brazil. Pará is the second largest territory in the federation, with an area equivalent to 14.7% of the national territory, covering a large part of the Brazilian Amazon (Venturieri; Nascimento Jr; Oliveira Jr, 2019).

Figure 1 – Spatial location of the study area



Source: Authors (2022)

The territory of Pará spreads over 1.2 million km² divided into 144 municipalities (IBGE, 2020), with 69% of the territory covered by tropical forests. It is completely inserted in the Amazon Basin, with diverse vegetation, made up of different formations that include terra firme forest, várzea, igapó, mangroves, várzea fields, terra firme fields, grasslands, mountain vegetation, and restinga vegetation (Braga, 1979).

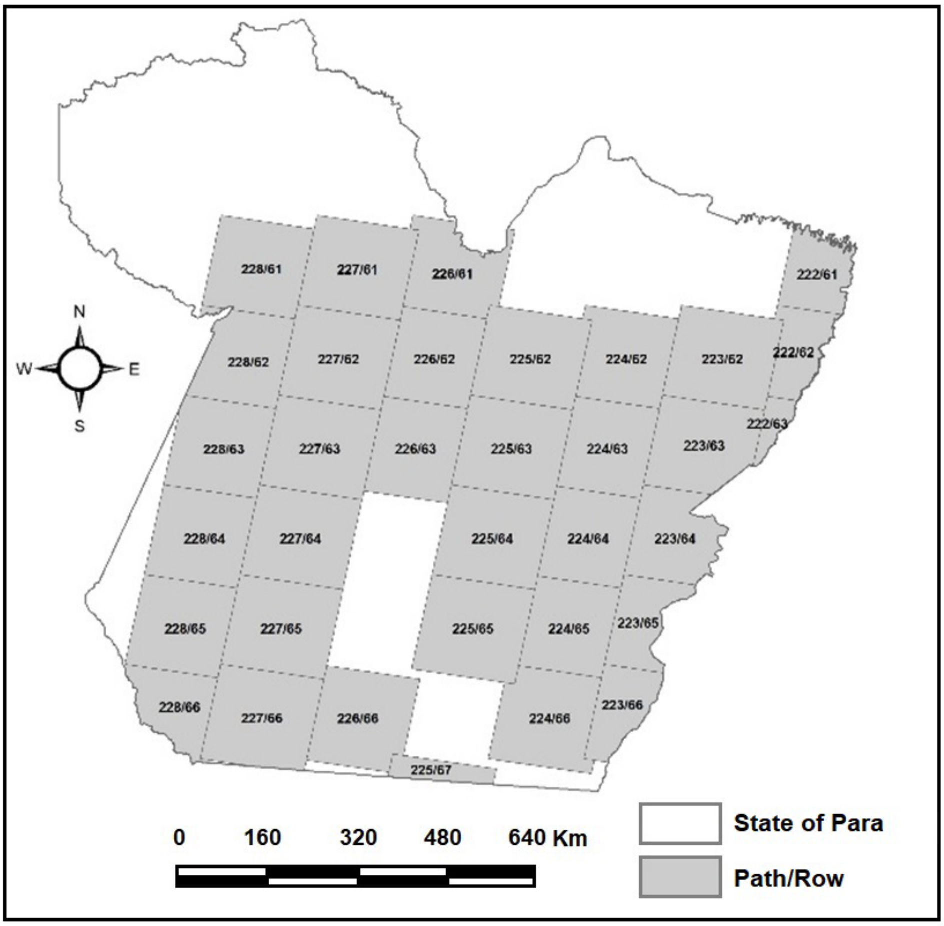
The study area has an Am-Monsoon climate, hot and humid throughout the year according to the Köppen classification (1937), with rainfall being the parameter with the highest heterogeneity and space-time variability (Loureiro *et al*., 2014). Total annual rainfall varies between 2,500 and 3,100 mm throughout Pará, characterized by rainy (December to May) and dry (June to November) seasons. The average annual temperature displays short seasonal variation with an average above 26°C (Alvares *et al*., 2013).

2.2 Database

The database employed in this study was provided by Matricardi *et al*. (2013) and Costa *et al*. (2019), which contained forest areas impacted by selective logging activities identified and mapped in 1992, 1996 and 1999 and in 2003, 2006, 2010 and 2014 by the studies, respectively. In addition, the selectively logged forests were mapped in 2018 using visual and semi-automatic analysis of 34 scenes from the Landsat-8 satellite (OLI), acquired between July and December 2018, selecting the images with the lowest percentage of clouds in the period (Figure 2). The images were obtained from the Google Earth Engine (GEE) platform database.

Moreover, the boundaries of Conservation Units and Indigenous Lands, obtained from the Brazilian Institute of Geography and Statistics, were used to measure the areas of selective logging within protected areas (Conservation Units and Indigenous Lands). In this case, we sought to verify the occurrence of illegal logging activities that potentially happened in these areas during the study period since they have only been permitted within the Conservation Units (e.g., National Forests) more recently in the form of Forest Concessions. The characteristics of the data set used in this study, including feature, format, and spatial resolution, are shown in Table 1.

Figure 2 – Path and Row of the 34 Landsat-8 scenes used to detect and map selectively logged forests in Pará state in 2018



Source: Authors (2022)

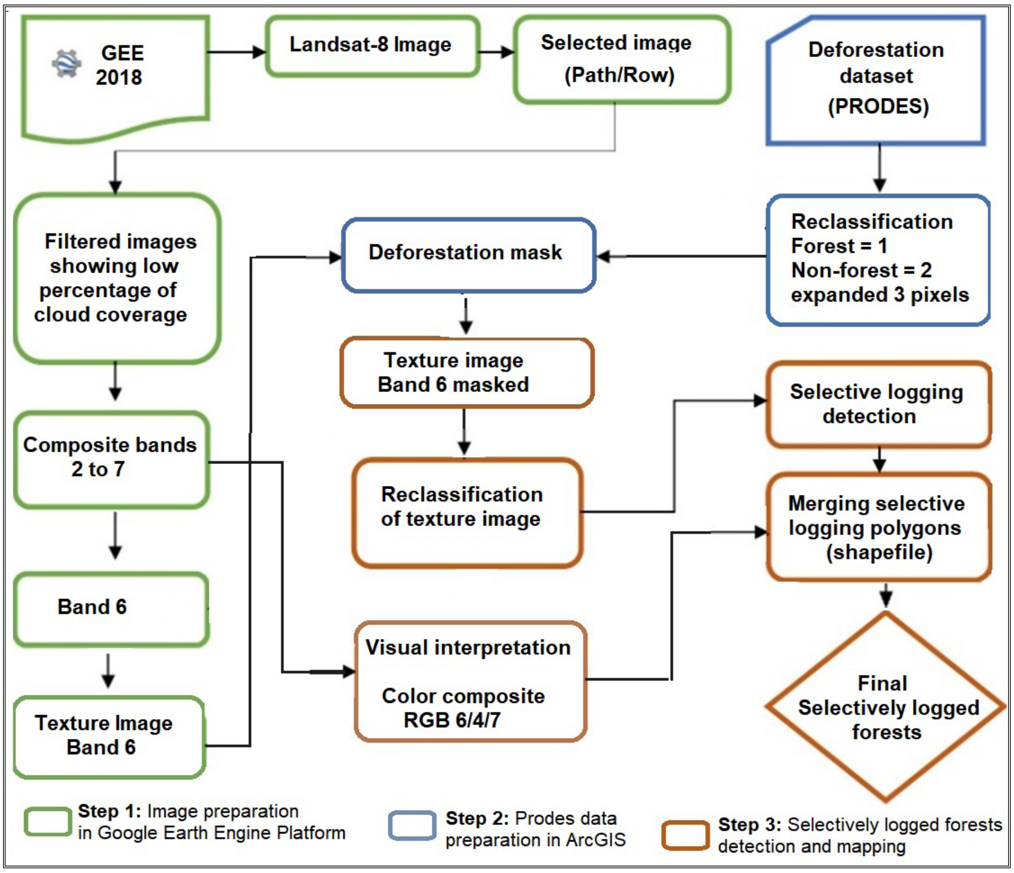
Table 1 – Geodataset used in this study

Data	Feature	Format	Resolution	Datum	Sources
Landsat images	matrix	.tif	30 m	WGS 84	GEE (2022)
Landsat WRS-2 Grid	polygons	.shp	-	WGS 84	USGS (2022)
Boundary of Pará	polygon	.shp	-	WGS 84	MMA (2022)
Conservation Units	polygons	.shp	-	WGS 84	ICMBIO (2023)
Indigenous Lands	polygons	.shp	-	WGS 84	FUNAI (2022)
Deforestation	polygons	.shp	-	WGS 84	INPE (2018)
Selective logging (1992, 1996 and 1999)	matrix	.tif	30 m	WGS84	Matricardi *et al*. (2013)
Selective logging (2003, 2006, 2010 and 2014)	matrix	.tif	30 m	WGS84	Costa *et al*. (2019)

Source: Authors (2022)

Figure 3 shows the acquisition and processing of Landsat-8 images to identify selectively logged areas in Pará state.

Figure 3 – Flowchart of the methodological approach applied to detect and map selectively logged forest areas in Pará state, Brazil



Source: Authors (2022)

To detect selectively logged forests in Pará in 2018, using Landsat-8 images, it was applied the methodology developed by Matricardi et al. 2005 in three stages: In the first stage, image search and processing procedures were carried out on the GEE platform, using date filters and cloud cover conditions. This stage used a Landsat-8 image collection from the OLI (Operational Land Imager) sensor, with surface reflectance, i.e., already corrected for the effects of the atmosphere and duly georeferenced (Collection 2, Level 2 Science Products). We also used a function that returns the images with the lowest percentage of cloud cover within the selected period: filter [ee.Filter.lt ('CLOUD_COVER,' 8)] on the GEE platform.

From the image collection of the period analyzed, bands 2 to 7 of the Landsat-8 satellite were composed. The composed images of the six spectral bands were used in different color compositions for inspection and visual delineation (detailed in the sequence) of the selectively logged areas. Band 6, which contrasts soil effects with the forest canopy and is more resistant to atmospheric effects (Matricardi *et al*., 2005), was used to generate the texture image by applying the GLCM (Gray Level Co-occurrence Matrix) filter available on the Google Earth Engine platform, using a movable window of 5 x 5 pixels. The filtered image allowed higher highlighting of selectively logged forests, being used to detect wood storage yards and forest roads since this technique segments the image and classifies the segments, providing sharper and more contrasting edges (Matricardi *et al*., 2005).

In the second stage of applying this methodology, we sought deforestation data from the Prodes Project (Monitoring Deforestation of the Amazon Forest by Satellite) for 2018. The deforestation data was reclassified into forest (areas with forest cover) and non-forest (including “cerrado” and deforested areas) to be used to mask the images so that only native forest areas could be analyzed. In the last stage, the RGB 6/4/7 color composition was used in ArcGIS® software, licensed to the University of Brasilia, to identify areas with visible impacts on the forest canopy caused by selective logging activities. Besides, woodyards and roads were segmented and extracted from the Landsat-8 band 6 texture images. A 180-meter buffer zone was applied around the forest infrastructure areas to estimate the area of forest impacted by logging activities, as suggested by Matricardi et al. (2005). Finally, the visual interpretation maps were composed with semi-automatic detection using texture imaging and the 180-meter buffer to make the final maps of the selectively logged forest areas, besides extracting the data supporting the research results. Further details of the methodology applied in this analysis are presented below.

2.3 Visual classification of forests impacted by selective logging

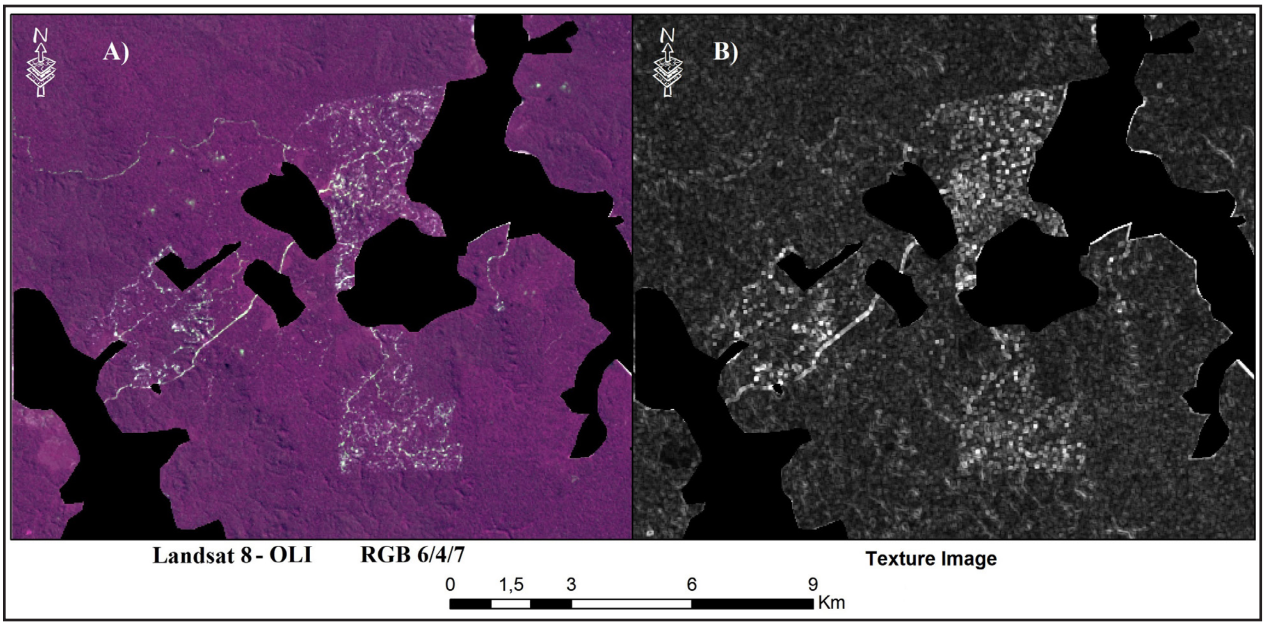
Deforestation data for the years 1992, 1996 and 1999 were obtained from the Tropical Rain Forest Information Center (TRFIC) and deforestation for the years 2003, 2006, 2010, 2014 and 2018 were acquired through the PRODES-INPE program. Deforestation data was reclassified as forest = 1 (all types of forest cover) and non-forest = 0 (other types of non-forest land cover and anthropized areas). The reclassified binary image (Forest and Non-forest) was used to mask the multispectral images, resulting in images containing only forest areas. In addition, the “expand” command available in the ArcGis “raster calculator” tool was used to expand the deforestation by three pixels over the forest areas, removing the edge effect.

The boundaries of the selectively logged forests showing visible patterns (yards, forest roads, and reduced reflectance of the vegetation in the forest canopy) were digitized manually on a computer screen using the RGB color composition of the spectral bands SWIR-1 (short wave infrared-1), Red, SWIR-2 (short wave infrared-2), with deforestation mask, supported with the texture images. The combination of these bands highlighted the logging yards and roads, which are perfectly visible in the image (Figure 4).

After identifying the principal infrastructure (woodyards and primary forest roads), 180-meter buffers were built around them to identify and estimate forest areas affected by selective logging activities but not detectable on satellite images (Matricardi *et al*., 2005).

The manually digitized selective exploitation (visual interpretation) and the texture filter were merged into a map in vector format, which was then converted into matrix format. By processing end, the data for each Landsat scene analyzed was projected onto the Sinusoidal projection. The projected Landsat scenes were merged into a final image (mosaic) containing the combination of the two techniques (visual interpretation and texture), which showed an overall accuracy of 92.9% (Matricardi *et al*., 2007).

Figure 4 – A) RGB color composition 6/4/7 (Landsat-8); B) texture image of band 6, scene 223/63, showing woodyards within selectively logged forests in Pará state on July 9, 2018.



Source: Authors (2022)

To facilitate the visualization and presentation of selective logging in Pará state, a grid of polygons measuring 225 km² each (15 x 15 km) was drawn up. By doing this, the percentage of selectively logged forest areas present in each grid polygon was calculated.

2.4 Inter-annual assessment of selective logging evidence in the forest

The data on selective logging between 1992 and 2018 in Pará state were overlaid on the data containing the boundaries of Conservation Units and Indigenous Lands. This operation was conducted to quantify the selective logging evidence inside protected areas.

In addition, the selective logging areas detected in the first year were overlaid in the subsequent years of this analysis. This methodological step sought to identify the persistence/recurrence of those areas or their conversion to other land uses (deforestation). The starting point was 1992 and was subsequently overlaid with selective logging from 1996, 1999, 2003, 2006, 2010, 2014 and 2018. Similarly, those layers from 1996 were overlaid in subsequent years. The same procedure was carried out for all the years of selective logging, totaling 28 overlays of those areas.

2.5 Net area estimates

The net increment of the logged forests was estimated on the overlapping polygons of selective logging. Overlapping areas were not counted twice, as polygon intersections were excluded, and non-overlapping areas were considered new logging areas. The areas of selective logging detected in 1992 were used as the basis for this analysis since no increase could be perceived for that year. The procedure of overlapping the areas was carried out sequentially for all the years of this analysis (1992 to 2018).

2.6 The relationship between selective logging and deforestation

The areas of selective logging were overlaid with the deforestation data produced by TRFIC and PRODES for 1996 and 1999 and for the years 2003, 2006, 2010, 2014 and 2018, respectively. These overlays were used to estimate the areas of selective logging that were deforested during the analysis period. Areas deforested in one of the years of the analysis were not computed in subsequent years of the analysis.

The Cox-Stuart test was applied to verify the existence of any data trend from selectively logged forests, using the R software, randtest package and the command cox.stuart.test () at a 5% significance level. The Cox-Stuart test or sign test consists of grouping the observations into pairs, where the differences are calculated by associating the signs "-" for negative values and "+" for positive values (MORETTIN; TOLOI, 2006).

The hypotheses tested were: H0: There is no trend (the numbers of positive and negative signs are the same); H1: There is a trend (the numbers of positive and negative signs are different).

3 RESULTS AND DISCUSSIONS

The use of remote sensing data and techniques makes it possible to detect selectively logged forests in the Amazon (Matricardi *et al*., 2007; Matricardi *et al*., 2010). This study estimated an average area of 10.462 km² ± 3.454 km² (Standard Deviation) of selectively logged native forests detected in the years analyzed between 1992 and 2018 (Table 2). The total area of selectively logged forests increased linearly between 1992 and 2003, from 2,409 km² in 1992 to 15,931 km² in 2003, an average of 8,571 km² ± 4,820 km² during that period. From 2006 onwards, the total area of selectively logged forests stabilized, with an average of 12,353 km² ± 267 km² between 2006 and 2018. In 2003, with 15,931.3 km² (Table 2), there was the largest area of forest impacted by selective logging activities in the period and study area, which preceded one of the years with the highest deforestation rate (27,772 Km2) in the Brazilian Amazon (INPE, 2023).

Table 2 – Forests selectively logged detected in Pará state in each year of this analysis, between 1992 and 2018

	Forests selectively logged (km2)							
Year	**1992**	**1996**	**1999**	**2003**	**2006**	**2010**	**2014**	**2018**
Total	2,409.0	5,093.0	10,851.1	15,931.3	15,441.7	13,139.1	10,760.3	10,069.3

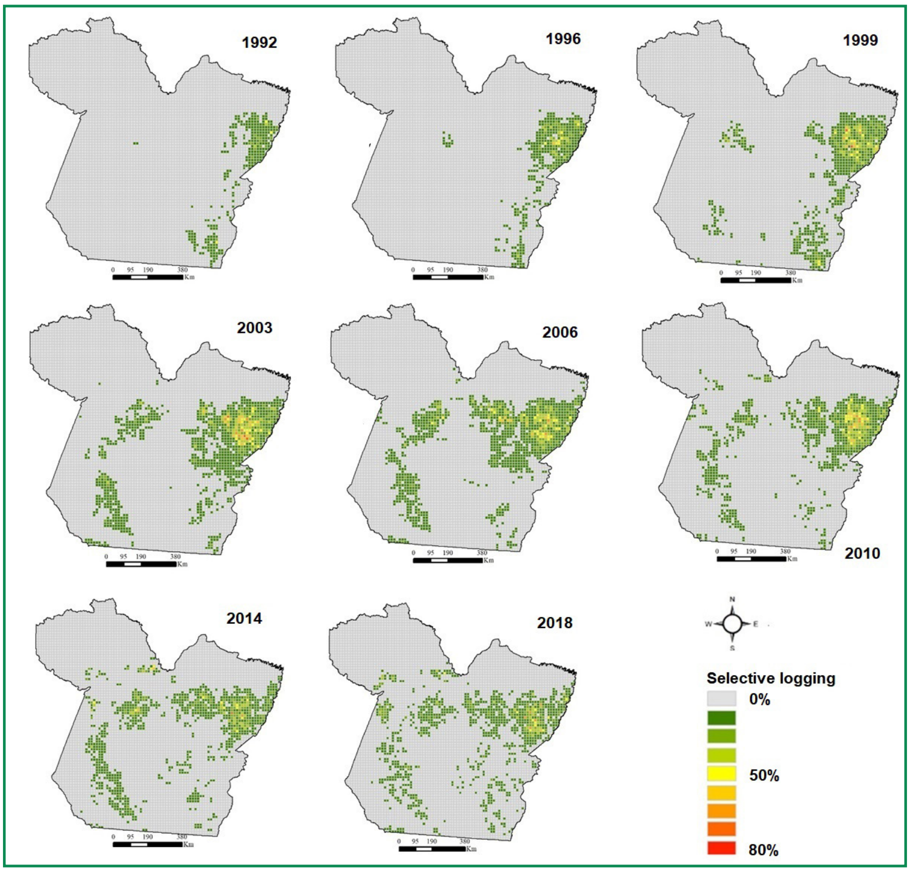
Source: Authors (2022)

The result of the Cox-Stuart test indicated a significant trend (p-value = 0.967, α = 0.05) in the growth of selective logging areas between 1992 and 2003. After this period, the Cox-Stuart test did not identify any significant trends (p-value = 0.625, α = 0.05) in the areas of selective logging detected between 2006 and 2018. In this sense, it is assumed that the total areas of selectively logged forests remained at the same levels between 2006 and 2018 in Pará state, with no overall upward or downward trends. The initial growth followed by stabilization of the total detected area of logged forests was also observed by COSTA (2019) in a study conducted for the entire Legal Amazon between 1992 and 2014.

The largest selectively logged forests detected during the study period were in northeastern Pará state. From 1999 onwards, selective logging was also expanded and intensified in the west and southwest Pará. This indicated a change in the spatial dynamics of logging activity, probably due to the depletion of raw materials (logs) from the forests located in the east of the state to regions with higher production potential in the native forests in the west and southwest of the state.

The spatial distribution trend of selectively logged forests observed in this study (Figure 5) indicated a migration from the logging centers of the 1990s to other centers in the west and southwest of the state after 2000. The observed spatial dynamics of selectively logged forest areas indicate a possible exhaustion of forest resources in older logging centers, with migration to new frontiers with higher natural potential and availability of timber resources in native forests.

Figure 5 – Spatial distribution of selectively logged forests detected in Pará state between 1992 and 2018



Source: Authors (2022)
In where: Selective logging was aggregated into a 225 km² polygon grid and represented as a percentage of the selective logging extent observed in each polygon

The forests exploited in the 1990s were mainly concentrated in the northeastern and southeastern mesoregions of Pará, a region known as the arc of deforestation. From the 2000s onwards, degradation began to spread to the southwest and lower Amazon mesoregions. Cardoso and Souza (2017), assessing the spatial distribution of unauthorized logging in the state of Pará, observed that most logging was concentrated in the northeast and southeast mesoregions of Pará (71%) and the rest in the lower Amazon (14%), southwest Pará (10%) and Marajó (4%).

3.1 Selective logging within Conservation Units and Indigenous Lands

The average amount of selective logging detected within conservation units (federal, state, and municipal) from 1992 to 2018 was 345 km². Until 1999, selective logging inside Conservation Units amounted to 57 km². However, in 2003, selective logging increased by more than 600 km². From 2014 to 2018, there was a 36% increase in forests impacted by logging activities. The largest forest areas employing selective logging in protected areas in Pará state were observed in 2003, 2006, and 2018 in the Jamanxim National Park and the Jamanxim, Altamira, and Trairão National Forests (Figures 6 and 7, Table 3).

Table 3 - Selectively logged forests detected in Pará state between 1992 and 2018 within protected areas (Conservation Units and Indigenous Lands)

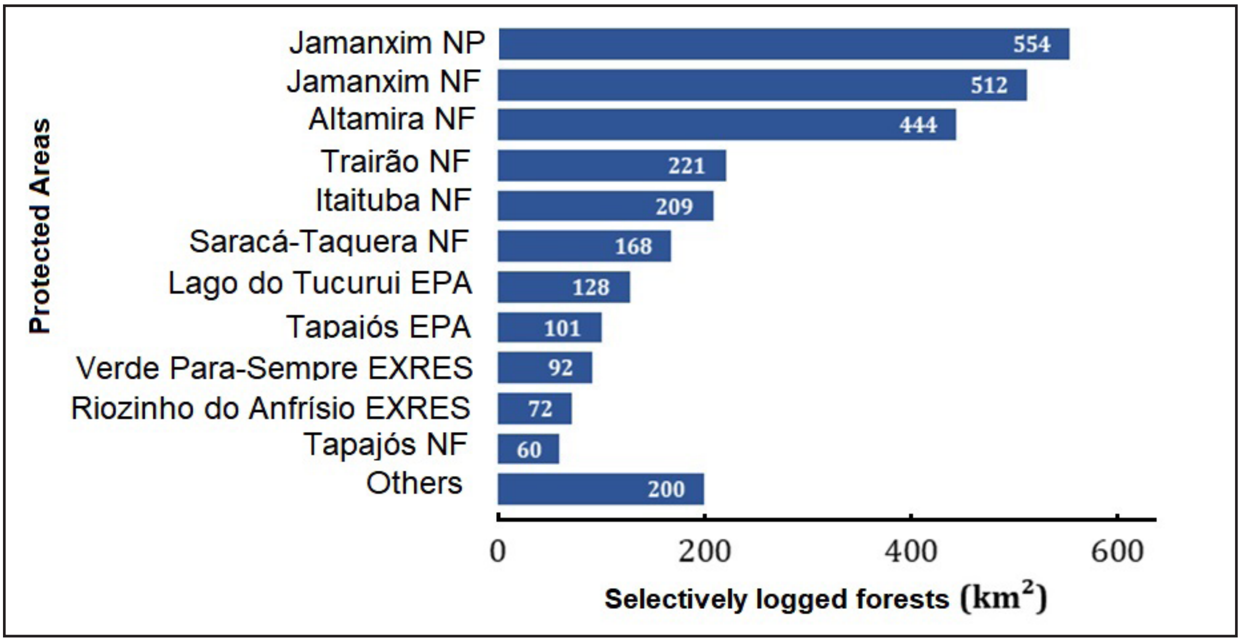
Protected Area	Selectively logged Forests (km²)							
	1992	1996	1999	2003	2006	2010	2014	2018
Conservation Units	2.33	1.32	53.40	730.26	570.20	391.54	428.30	584.55
Indigenous Lands	9.09	3.50	180.25	226.78	466.87	344.50	486.55	717.46

Source: Authors (2022)

The National System of Conservation Units establishes that only indirect use of natural resources is allowed within fully protected conservation units, except for cases provided for by law (BRASIL, 2000). In this study, it was observed that six Fully Protected Conservation Units (Jamanxim National Park, Rio Novo National Park, Nascente da

Serra do Cachimbo Biological Reserve, Terra do Meio State Ecological Station, Gurupi Biological Reserve, and Serra dos Martírios/Andorinhas State Park) showed selectively logged forest areas during the analysis period, in this case illegal, unauthorized logging. Although these areas have higher restrictions on their direct use, they are eventually more affected, as they are in regions under higher anthropic pressure in the Amazon (NOLTE et al., 2013). The cases of selective logging in National Forests may be related to the forest concession processes implemented in recent years by the Brazilian Forest Service in states of the Brazilian Amazon. In Pará state, the Saracá-Taquera National Forest (concession from 2010), the Crepori National Forest (concession from 2014), the Altamira National Forest (concession from 2015), and the Caxiuanã Forest (concession from 2016) has been considered to forest concession carried out by the Brazilian Forestry Service (BRASIL, 2021) (Figure 6).

Figure 6 – Total area of selectively logged forests detected within Conservation Units in Pará state between 1992 and 2018

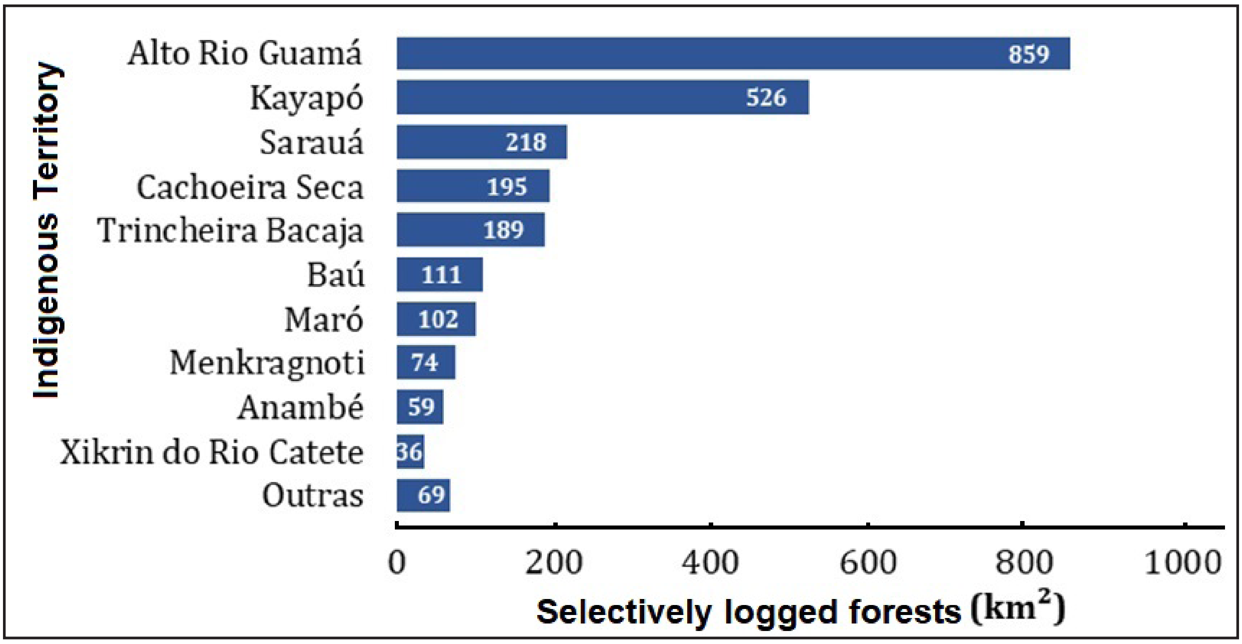


Source: Authors (2022)

The areas of forest selectively logged within Indigenous Territory (IT) in the Pará state totaled 466.9 km², 486.6 km², and 717.5 km² in 2006, 2014, and 2018, respectively, indicating an increase of 54% between 1992 and 2018. In this case, they are illegal activities without prior authorization and the technical monitoring and supervision required in areas of sustained forest management.

The Alto Rio Guamá IT, located in the northeastern mesoregion of Pará state, had the largest area of selectively logged forest (35%). This was followed by the Kayapó IT (22%), the Sarauá IT (9%), and the Cachoeira Seca IT (8%), corresponding to 74% of the total area of selective logging within ITs in the state of Pará between 1992 and 2018 (Figure 7).

Figure 7 - Total area of selectively logged forests detected within Indigenous Territories in Pará state between 1992 and 2018



Source: Authors (2022)

We estimated the areas of selective logging within Protected Areas (PAs) and Indigenous Territories (ITs) corresponded to 3.3% and 2.9% of the total forests logged in Pará, respectively, during the period studied. Therefore, Conservation Units were the areas most impacted by selective logging activities in the state, compared to Indigenous Lands. On the other hand, when analyzing the impacted forests by selective logging inside protected areas throughout the Brazilian Amazon, studies have shown that most of the degraded areas occurred inside Indigenous Lands (Matricardi *et al*., 2007; Cardoso; Souza Jr, 2018; Moretti *et al.*, 2020).

This difference between what was observed within the PA and IL in this study and others previously cited may be related to the four National Forests under forest concession in Pará state since 2010, under the responsibility and control of the Brazilian Forest Service. Therefore, logging within these areas follows the principles of sustainability and resource conservation (Cardoso; Souza Jr, 2018). Besides, Moretti *et al*. (2020) suggest that the reason why most selective logging takes place inside PAs may be related to the proximity of the logged to deforested areas and that this proximity facilitates the entry of illegal logging agents who formalize verbal contracts with squatters to exploit timber resources.

When checking for trends in the data series within protected areas analyzed using the Cox-Stuart test (Table 3), no significant trends were identified (p-value = 0.625 for Conservation Units and p-value = 0.125 for Indigenous Lands) for selective logging in PA and IL between 1992 and 2018. This is indicative that logging activities tend to remain like the levels observed in this study within protected areas. Although the increase in logged forest areas was not statistically significant, it reveals that protected areas are exposed to illegal logging since most of these logging activities are usually considered illegal, especially within ILs. Studies carried out in the Amazon have displayed this behavior of increased degradation in protected areas, being related to proximity to deforested areas, roads, and illegal access routes (Pedlowski *et al*., 2005; Matricardi *et al.*, 2007; Costa *et al*., 2019; Moretti *et al*., 2020).

3.2 Recurrence and persistence of selective logging activities

It is estimated that 51.4% of the wood selectively logged during the period and study area was considered recurrent or persistent. This is equivalent to a total of 43,046.5 km² with an annual average of 1,655.6 km² (Table 4). The areas were reckoned persistent when detected over more than a consecutive year without conversion to another land use (deforestation).

Table 4 - Selectively logged forests detected on a recurring basis in Pará state between 1992 and 2018

Detection Year	Recurrence of selectively logged forests (km²)						
	1996	**1999**	**2003**	**2006**	**2010**	**2014**	**2018**
1992	132.91	268.54	373.58	311.87	341.42	124.35	157.42
1996	-	1,919.20	942.98	854.70	1,052.86	632.02	565.59
1999	-	-	2,703.02	1,746.02	2,045.83	1,344.18	1,280.47
2003	-	-	-	4,039.68	3,866.00	1,792.48	1,759.18
2006	-	-	-	-	5,328.06	1,628.46	1,639.01
2010	-	-	-	-	-	2,050.45	1,815.28
2014	-	-	-	-	-	-	2,330.85
Total	132.91	2,187.74	4,019.58	6,952.27	12,634.17	7,571.94	9,547.80

Source: Authors (2022)

The broadest areas of recurrent selective logging were estimated in 2010 and 2018, involving 12,634.17 km² and 9,547.8 km² of forests logged in previous years, respectively. This indicates a possible shortage of raw material (logs) in recent years that forced loggers to return to or revisit previously logged areas, contributing to detecting an increase in the recurrence of previously logged forests in possible new forest management cutting cycles.

It was also estimated that the oldest areas of selectively logged forests detected on a recurring basis are smaller than the most recently logged forests. This indicates the occurrence of new logging cycles in areas logged in previous decades.

Depending on logging intensity, the impacts of forestry activities remain visible for around 3 to 4 years, and, considering severe logging effects, soil exposure can be observed even after five years of logging (Matricardi *et al*., 2005). Thus, although the forest can recover after this time interval, one of the reasons why the impacts of selective logging remained visible throughout the period studied is that loggers revisit logged areas at shorter intervals to remove the remaining species with lower commercial value from the forest (Uhl *et al*., 1997; Lima *et al.* 2019; Moretti *et al*., 2020).

Unlike deforestation, forest impacts caused by selective logging can occur with varying frequency and intensity in the same area, and several years after logging, forest impacts can be detected in satellite images that overlap spatially (Matricardi *et al*., 2020). Over time and with the frequent exploitation of a forest, the extent of the impacts of selective exploitation increases, and this pattern of recurrent exploitation in consecutive years can result in greater intensity of forest fragmentation (Broadbent *et al*., 2008).

3.3 Increase in selectively logged forests

The increase in selectively logged forest areas detected in Pará between 1992 and 2018 in this study totals 52,455 km², with an annual average of 2,018 km² (Table 5). The highest increases were observed in the 1999-2003 and 2003-2006 periods (11,912 km² and 9,860 km², respectively). There was a significant upward trend in the increase between 1992 and 2003, followed by a period of reduction (between 2003 and 2006) and stabilization of the growth at around 5,600 km² per period analyzed between 2006 and 2018.

Table 5 - Increase of areas of selectively logged forests detected in Pará state between 1992 and 2018

Period	Increase in selectively logged forests (km²)
1992-96	4,956.52
1996-99	8,703.85
1999-03	11,911.66
2003-06	9,859.67
2006-10	5,311.09
2010-14	6,427.04
2014-18	5,284.68
Total	52,454.51

Source: Authors (2022)

Despite increases in the areas of forest disturbed by selective logging activities between 1992 and 1999, followed by a period of stabilization of annual increases between 2003 and 2018, the IBGE data series (2021) indicates a reduction in the volume of timber extracted in Pará between 1992 and 2018. One explanation for the increase and its maintenance in logged areas without necessarily an increase in production is the possible flaws in the control and inspection of the state timber production. Besides, selectively logged forests may have been revisited in new cutting cycles, with lower productivity than the first cycle, which is usually much more productive than subsequent cycles.

3.4 Selective logging and deforestation

It is estimated that 16,916.4 km² of selectively logged forests were cleared between 1992 and 2014 (Table 6). In 2006, 2010, and 2018, large areas of selectively logged forests were deforested in the years following their exploitation, with the largest one detected in 1992 being deforested after seven years of logging.

Table 6 – Areas of selectively logged forests detected in Pará state between 1992 and 2018, subsequently deforested (between 1996 and 2018)

Detection year	Selectively logged and deforested forests (km²)						
	1996	**1999**	**2003**	**2006**	**2010**	**2014**	**2018**
1992	320.4	564.2	300.2	223.3	126.4	41.0	44.6
1996	-	832.8	571.9	357.9	177.8	101.6	128.2
1999	-	-	1,525.7	989.1	550.1	304.0	393.8
2003	-	-	-	2,038.3	778.9	561.6	678.7
2006	-	-	-	-	1,533.9	479.2	718.7
2010	-	-	-	-	-	1,324.4	523.5
2014	-	-	-	-	-	-	726.4
Total deforested	320.4	1.397.0	2,397.8	3,608.6	3,167.1	2,811.7	3,213.8
Total detected exploited selectively	5,093	10,851	15,931.3	15,441.7	13,139.1	10,760.3	10,069.3
% selective logging deforested	6.3%	12.9%	15.1%	23.4%	24.1%	26.1%	31.9%

Source: Authors (2022)

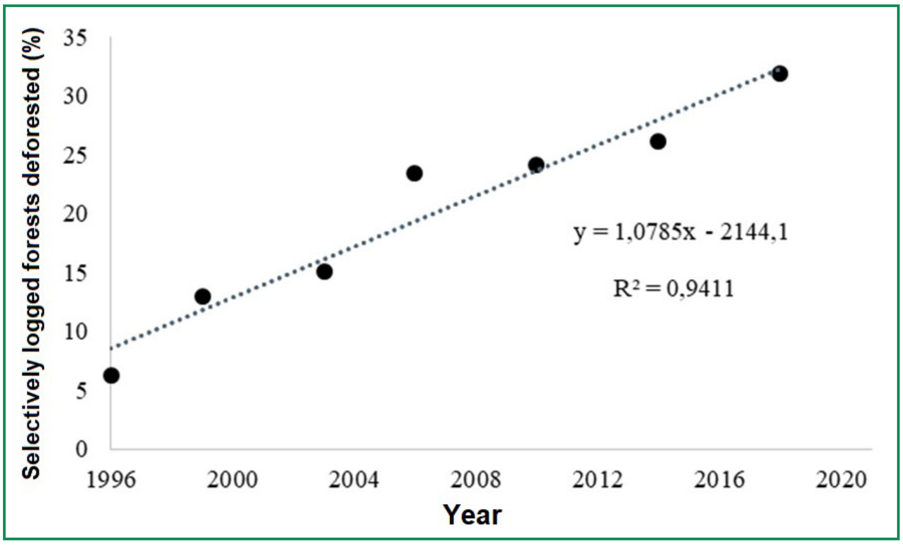
In where: based on deforestation datasets provided by the Tropical Rain Forest Information Center (TRFIC) and Legal Amazon Deforestation Monitoring Project by satellite (PRODES).

Nepstad *et al*. (1999) stated that the degradation due to selective logging and fire are the principal causes of deforestation in the Amazon. Asner *et al*. (2005) estimated an increase from 12,075 km^2 to 19,823 km^2 of forest degraded by selective logging between 1999 and 2002, representing 19% of the total area of selective logging detected was deforested three years after the degradation. The results of this study show that 13% of the total area of selective logging detected in 2003 was deforested three years later. In addition, there was a reduction in deforested areas in 2014 compared to previous years. The percentage of 31.9% of the forests selectively logged between 1992 and 2014 were cleared between 2015 and 2018.

The total degradation observed for selectively logged forests compared to deforestation during the same period in Pará reveals that the degradation exceeded deforestation in some years. Thus, as observed in this study, researchers found that between 1992 and 2014, 337,427 km^2 of forests were degraded, and 308,311 km^2 were affected by deforestation (Matricardi *et al*., 2020). The authors evaluated different forest degradation factors, which included selective logging, fires, and forest fragmentation. However, selective logging and fires contributed to 43% of the degradation, nearly half of the area deforested in the same period. Thus, degradation caused by selective logging adds more damage to forests than was reported for deforestation alone in the same study period and can be considered a significant form of landscape and ecosystem alteration (Matricardi *et al*., 2020).

There was, in general, a significant upward trend in the percentage of selectively logged forests that were deforested during the study period, from 6.3% in 1996 to 31.9% in 2018. The graph below made it possible to identify the temporal behavior of deforested areas that occurred after selective logging. Over the years, there has been an increase in deforestation rates in selectively logged forests, with a linear growth trend. The coefficient of determination (R^2) explained 94% of the variance. The trend line equation allowed values of the dependent variable y (% of selective logging deforested) to be estimated from values of the independent variable x (year) (Figure 8).

Figure 8 – Percentage variation of selectively logged forests detected between 1992 and 2018, following subsequent deforestation (between 1996 and 2018) in Pará state



Source: Authors (2022)

Based on this equation, it was possible to predict that in less than 15 years, half of the selectively logged area will be deforested in the study area and that in 58 years, practically all of the selectively logged area will be deforested in subsequent years, i.e., it is expected that by 2034 half of those areas in Pará will be deforested, with virtually all of the selectively logged area detected in this study deforested by 2080. Selective logging is a contributing factor to forest degradation in the area studied. In addition, other factors such as forest fires and the opening of official roads also contribute to this deforestation process (Matricardi *et al*., 2010, 2013; Pinheiro *et al*., 2016; Costa *et al*., 2019).

Nevertheless, it is fundamental to note that the projection only considered areas that were selectively logged, and other factors besides selective logging also contribute to this process of degradation and deforestation in the state of Pará. Based on mapping land cover changes over the last decade, Brochado (2017) considered three scenarios to draw up a deforestation forecast for Pará until 2030. The results show that the deforested area projected for 2030 was 689,160.37 km², assuming an optimistic scenario, 754,960.88 km² for a pessimistic one, and 741,947.62 km² for a trend scenario. Based on these scenarios, the PAs and ILs alone could not prevent the advance of deforestation, and more effective environmental command and control policies are needed in these areas.

4 CONCLUSIONS

Although no significant growth trends were observed in the data series analyzed, the results of this study indicate an increase in the areas of selectively logged forests, especially in the last two decades of the study period. Changes were also observed in the spatial dynamics of selective logging, which has expanded into new frontiers of Pará state while maintaining a definite concentration in old frontiers in the region known as the arc of deforestation.

Observations from the last decade show that forests impacted by logging activities have been detected more frequently in deforestation frontier regions in Pará. This migration may be associated with the greater availability of raw materials and the expansion of the agricultural frontier, besides new areas that have not yet been exploited. Based on the overlapping of logged forest areas, the results allow us to conclude that there has been an increase in the recurrence of selective logging.

Approximately 20% of the total logged forest was deforested in the study area and period. Selective logging does not seem to be the principal precursor to deforestation in Pará, but it has shown growing trends in recent years and has contributed to the deforestation process. It was observed that selective logging has a spatially distinct and independent distribution from deforestation. It's worth saying that the areas that are part of the deforestation process are mostly previously selectively logged (forest species with better timber potential). Otherwise, it would be economic nonsense for rural producers. This deforestation process was not considered in this analysis, and selective logging was mainly identified as a separate and independent activity from deforestation.

The results of this study indicate that the impacts of selective logging within protected areas have not been significant from a spatial point of view compared to the area of the entire state. Nonetheless, it has remained constant over the period studied, with the majority being illegal activities. Activities within Indigenous Lands that are not under a management or concession regime formally authorized by the responsible bodies stand out here.

Overall, the importance of mapping the extent of selective logging stands out, as this knowledge allows us to assess the impact of different patterns of land cover change, besides helping decision-makers to reinforce forest conservation /preservation actions, mainly because the Amazon rainforest plays a crucial role in providing ecosystem services of great importance at local, regional, national and global levels.

ACKNOWLEDGEMENTS

The authors thank the Higher Education Improvement Coordination (CAPES), the National Council for Science and Technology, and the Graduate Program in Forestry Sciences at the University of Brasília (UnB).

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How to quote this article

SOUZA, J. V.; MATRICARDI, E. A. T.; PEDLOWSKI, M. A.; MIGUEL, E. P.; PEREIRA, R. S. Spatio-temporal assessment of selective logging in Pará state, Brazil. **Ciência Florestal**, Santa Maria, v. 34, n. 2, e71255, p. 1-29, 2024. DOI 10.5902/1980509871255. Available from: https://doi.org/10.5902/1980509871255. Accessed in: day month abbr. year.