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Papers

Analysis of the Land Use and Land Cover and the Normalized Difference Indexes of Vegetation and Water within Indigenous Lands and Surrounding Areas in the Brazilian Amazon Basin

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Abstract
The majority of Brazilian Indigenous lands, more than 98%, are found in the Amazon region. They are a major barrier to the advance of deforestation in this region. The Amazon region and its vast biodiversity have suffered from the advance of agriculture and illegal and legal occupations that do not consider regional environmental characteristics. This study analyzed changes in vegetation between 1985 and 2020, within and around Indigenous lands in the Brazilian Amazon Basin. The analysis was conducted using the land use and land cover classification, the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Land Surface Temperature (LST). Results showed that Indigenous lands and their surroundings, located far from agricultural properties and close to other Indigenous lands or federal Conservation Units (UCs), maintained the conservation of vegetation, temperature, and soil moisture in their internal and surrounding areas. Indigenous lands adjacent to areas of agricultural expansion, while still conserving their vegetation, experienced changes in their surroundings. Soybean fields and pasture areas have replaced the forest, which increased LST. This study showed the resilience and importance of Indigenous lands in protecting and preserving the Amazon biome and its vast biodiversity.

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INTRODUCTION

Culture and knowledge from Indigenous peoples help to increase and conserve biodiversity. Lima and Mendes (2015) claimed that more than 98% of the Indigenous lands are found in the Amazon region and they are the primary barrier to the advance of deforestation in the region. According to Souza and Garcia (2021), the higher rates of biodiversity in the Amazon region are found in Indigenous lands.

Amazon deforestation has intensified since the 1970s due to the region's economic development (Folhes *et al.*, 2012). Currently, the removal of vegetation cover in the Amazon is reaching critical levels. Although the Amazon Rainforest has been devastated for several reasons, Fearnside (2022) stated that agricultural and livestock activities are the primary cause.

The Amazon region covers the highest biodiversity of fauna and flora species worldwide, including endemic species and others still unknown (Prado, 2021). Deforestation causes huge losses. Prado (2021) pointed out land and water degradation in addition to biodiversity loss.

Evapotranspiration in the Amazon biome plays a crucial role in rainfall formation throughout the country (Fisch *et al.*, 1998). Deforestation decreases the precipitation rate and increases soil vulnerability, influencing soil erosion and siltation of rivers. Sediment accumulation causes the river to lose depth, and this loss of depth expands the river width causing flooding and increasing water temperature and evaporation rate due to higher solar irradiation per unit area (Spracklen; Garcia-Carreras, 2015). Climate change and sediment accumulation influence river biodiversity. Continuous and growing changes in land use and land cover in the Amazon region can gradually lead to higher temperatures and drier conditions in the region, reaching levels that impact the presence of dense vegetation (Webler *et al.*, 2013; Nascimento *et al.*, 2020).

Indigenous lands and conservation units (UCs), which help in forest conservation, are constantly threatened by invasions (Celentano *et al.*, 2018). Amazon Rainforest degradation is the main threat to Indigenous communities, whether due to violent conflicts or natural resource unavailability (de Oliveira Dias; Dias, 2020).

Since Portuguese colonization, Indigenous peoples have experienced losses and conflicts (de Oliveira Dias; Dias, 2020). Indigenous lands become more vulnerable to illegal occupations due to the lack of land demarcation. Basta (2023) stated that Kayapó and Munduruku indigenous lands in Pará and Yanomani indigenous lands in Roraima are the most affected by illegal mining, and, consequently, by mercury contamination caused by mining.

Indigenous peoples fight for their land preservation and demarcation. The nature preserved by Indigenous peoples benefits all of us, but a few people are aware of this. There are several sustainable ways for a state's development, and everyone can benefit (Lima; Mendes, 2015).

Deforestation, land use and land cover, environmental impact, and other topics are evaluated and identified through remote sensing and geographical information systems. Information from these tools is essential in environmental monitoring studies since graphics, tables, and maps can be available to follow land use and spatial analysis over time (Pacheco, 2016). Georeferenced information is considered in this study, which provides valuable insights into the importance of Indigenous lands in the Brazilian Amazon Basin in preserving the Amazon ecosystem.

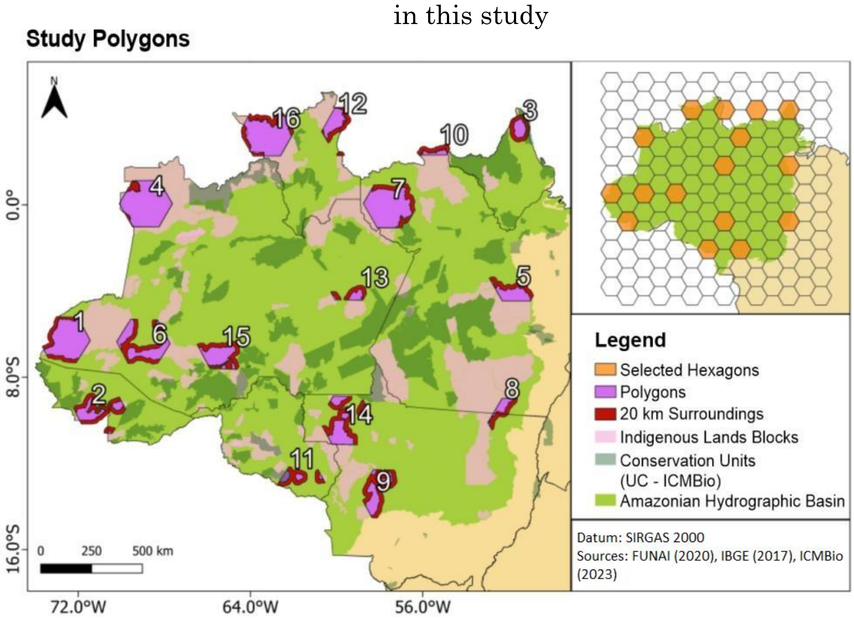
This study analyzed spatial changes in land use and land cover, NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and LST (Land Surface Temperature) between 1985 and 2020 considering areas within and around Indigenous lands in the Brazilian Amazon Basin.

MATERIAL AND METHODS

Study Area

The Brazilian Amazon Basin is located in northern Brazil (Figure 1). It fully covers the states of Acre, Amapá, Amazonas, Rondônia, and Roraima, while partially covering Mato Grosso and Pará. The Amazon region concentrates the highest number and the largest Indigenous lands, which can constitute real blocks. In this study, the borders between adjacent Indigenous lands were not considered, focusing on blocks of Indigenous lands. Since the study area covers an extensive region, just some blocks of Indigenous lands were analyzed. In the QGIS software, the Brazilian Amazon Basin was divided into several hexagonal grids, and 16 hexagons were selected using systematic random sampling. Only the blocks of Indigenous lands within these 16 hexagons were studied and denominated polygons (Figure 1). The UCs were not included in these blocks of Indigenous lands. Land use and land cover data, between 1985 and 2020, were analyzed and classified in the regions inside Indigenous lands intersecting the polygons and in a 20-km buffer zone around these Indigenous lands. The same was conducted on NDVI, NDWI, and LST data. According to Rodriguez *et al.* (2013), similar studies adopted a 10-km buffer zone. However, since each polygon area is extensive, a 20-km buffer zone, double the conventional one, was selected.

Figure 1 - Methodological procedure and polygons considered in this study



Source: The authors (2024).

Land Use and Land Cover

MapBiomas is a collaborative network for geoenvironmental research to map annual land use and land cover in Brazil and monitor territorial changes (MapBiomas, 2019). Geographical data from MapBiomas enables us to conduct several studies on land use and land cover in any part of the country.

The land use and land cover history in the polygons and its surroundings in the Brazilian Amazon Basin was developed using RStudio software. In this software, a script was created considering as input data the land use and land cover data extracted from MapBiomas and the geographical data of Indigenous lands (polygons). Statistical charts with MapBiomas classification (Collection 7) were obtained for each polygon between 1985 and 2020. In addition, a 20-km buffer zone around the Indigenous lands in each polygon was created, and the land use and land cover classification was extracted to compare with regions inside Indigenous lands.

Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Land Surface Temperature (LST)

The NDVI, NDWI, and LST were selected to analyze the quality of vegetation in the study area. Lopes and Moura (2013) stated that NDVI images enable us to monitor vegetation phenology on a temporal and spatial scale. Brenner and Gusselli (2015) explained that the NDWI methodology can detect water bodies while minimizing other targets, following the same reasoning as NDVI. The NDWI associated with LST can delimit areas undergoing drought, helping to understand ecosystem changes (Lopes; Moura, 2013).

These indexes were applied using a script in Google Earth Engine. Polygon vector and buffer vector were processed through script along with Landsat images, applying appropriate atmospheric corrections. Therefore, a spreadsheet was generated for each index and each polygon (16 polygons) and its buffer (16 buffers) between 1985 and 2020.

Each polygon and its respective buffer were placed in the same spreadsheet (e.g., polygon 9 for NDVI and buffer 9 for NDVI), in which the polygon represents the inside Indigenous lands and a 20-km buffer zone around Indigenous lands corresponds to the outside Indigenous lands. Forty-eight spreadsheets were created, of which 16 were for NDVI, 16 for NDWI, and 16 for LST. Data were organized considering monthly and annual dates close and compatible with regions inside and outside Indigenous lands (e.g., Inside Indigenous Lands January 14, 1999, and Outside Indigenous Lands January 16, 1999). After data processing, the Mann-Whitney U test was applied using a script in the RStudio software to verify their statistical significance and then select data for analysis.

Normalized Difference Vegetation Index - NDVI

NDVI is widely known and used and is obtained by satellite or drone images. It is calculated by the difference between near-infrared and red bands, normalized by the sum of these bands (Zanzarini *et al*., 2013), as given by Equation 1. In this study, the red bands were B3 from Landsat 4 and 5 missions and B4 from Landsat 8 missions, while the infrared bands were B4 from Landsat 4 and 5 missions and B5 from Landsat 8 missions. NDVI indicates the amount and condition of vegetation, ranging from -1 to 1 (Boratto *et al*., 2013).

$$NDVI = \frac{NIR-RED}{NIR+RED} \qquad \text{Eq. [1]}$$

Where:

RED = red spectral reflectance;
NIR = near-infrared spectral reflectance.

Normalized Difference Water Index - NDWI

The NDWI was proposed by McFreets (1996). It is calculated by the ratio of near-infrared spectral data (B4 from Landsat 4 and 5 missions and B5 from Landsat 8 missions) and green spectral data (B2 from Landsat 4 and 5 missions and B3 from Landsat 8 missions), as given by Equation 2 (Pereira *et al*., 2018). An NDWI>0 suggests the presence of wet bodies (water) and an NDWI<0 indicates more likely dried bodies (Rebouças *et al*., 2019).

$$NDWI = \frac{VIR-NIR}{VIR+NIR} \qquad \text{Eq. [2]}$$

Where:

NIR = near-infrared spectral reflectance;
VIR = green spectral reflectance.

Land Surface Temperature – LST

The LST is an essential parameter in several environmental research fields. The LST determined by Equation 3, proposed by Bastiaanssen and Bakker (2000), can be applied to heat island characterization, degraded areas detection, and entomological research (de Paiva *et al*., 2024). Thermal infrared bands of B6 from Landsat 4 and 5 missions and B10 from Landsat 8 missions were used. Emissivity was calculated based on NDVI images, obtained in Section 3.2.1, and using Equation 4 (Lopes *et al*., 2010).

$$LST = \frac{1260}{\ln\left(\frac{61{,}6}{L_{TM}}+1\right)} / \mathcal{E}^{\,0{,}25} \qquad \text{Eq. [3]}$$

Where:

L_{TM} = thermal infrared radiance;
ε = emissivity.

$$\varepsilon = 1{,}009 + 0{,}04Ln(NDVI) \qquad \text{Eq. [4]}$$

Mann-Whitney U test

Mann-Whitney U test is applied to two independent samples when data do not follow a normal distribution (Silva; Grácio, 2017). This test verifies if average values in Group A (inside Indigenous lands) are higher than average values in Group B (outside Indigenous lands) (Silva, 2007). The test evaluates the extent to which data from these two groups are interweaved after sorting (Silva, 2007; Silva; Grácio, 2017). The test statistic is given by Equation 5:

$$W = U_m - m.n \qquad \text{Eq. [5]}$$

Where:

W = test statistic;
m = sample size related to the first group;
n= sample size related to the second group;
S_m = rank sum for the first group.

Before applying Equation 5, the value of U_m must be obtained by Equation 6.

$$U_m = S_m - \frac{1}{2} m\,(m+1) \qquad \text{Eq. [6]}$$

This calculation was automatically performed using average values for each sample in space-time, in a script in the RStudio software, generating the statistical charts and the w and p-value for all 48 spreadsheets.

RESULTS AND DISCUSSION

This section presents the values obtained in the Mann-Whitney U test. It verified whether there was a significant statistical difference between the sets of data. It was applied to the 48 spreadsheets. The data were statistically significant considering a p-value<0.05. Six out of the 16 polygons were analyzed (highlighted in Table 1) based on significant overlapping values among the three indexes. An interpretive table described by Melo *et al.* (2011) and Rebouças *et al.* (2019) was used to analyze NDVI and NDWI in the polygons.

Table 1 - Mann-Whitney U test application

	NDWI		NDVI		LST	
POLYGON	**W**	**p-value**	**W**	**p-value**	**W**	**p-value**
P1	17193	0.02306	65284	4.41E-04	22568	0.04215
P2	24293	0.1049	46385	0.9352	54509	0.0757
P3	882986	0.5029	855765	0.4306	42414	0.915
P4	1981	0.001324	541.5	0.1234	797	3.07E-05
P5	1861.5	< 2.2e-16	41146	< 2.2e-16	1453	3.28E-02
P6	15312	< 2.2e-16	665	< 2.2e-16	6098	2.41E-04
P7	272	3.22E-10	1401	7.53E-06	466	6.62E-05
P8	1538148	0.06556	1650400	0.07171	38827	0.4869
P9	155228	7.49E-06	442188	0.009446	13938	0.0003471
P10	2523595	2.84E-11	3412400	< 2.2e-16	41437	0.8993
P11	125966	< 2.2e-16	507566	< 2.2e-16	69554	< 2.2e-16
P12	125966	< 2.2e-16	703547	0.01624	26806	0.2453
P13	999868	2.71E-03	1245860	7.34E-06	39374	0.8122
P14	580941	0.000273	696582	0.0001304	55545	0.4704
P15	1804196	0.1287	2096666	3.68E-09	38798	0.2881
P16	242726	< 2.2e-16	1186914	< 2.2e-16	10916	0.08005

Source: The authors (2024).

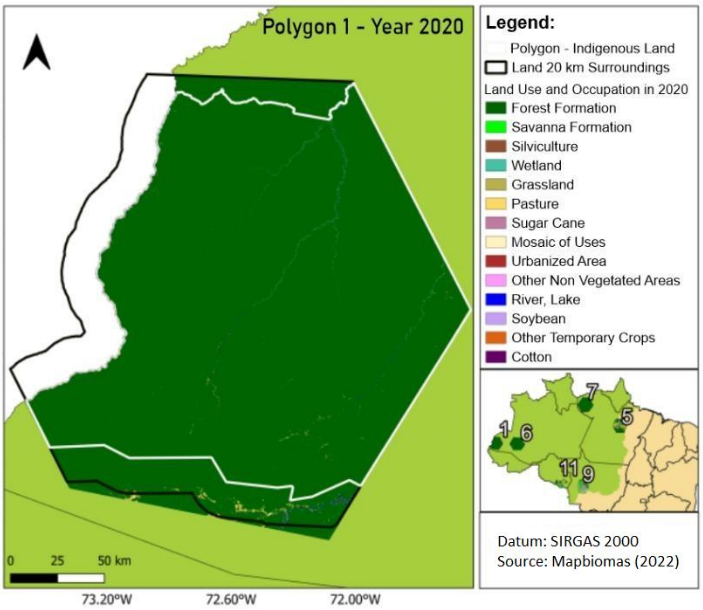
Polygons 1, 6, and 7

Polygons 1, 6, and 7 presented similar results due to the location of each one and its surroundings. Domingues and Bermann (2012) explained that Amazon areas far from the border between the Amazon and Cerrado biomes, such as these polygons, are more preserved since agribusiness has not reached them.

Land use and land cover in polygons 1, 6, and 7

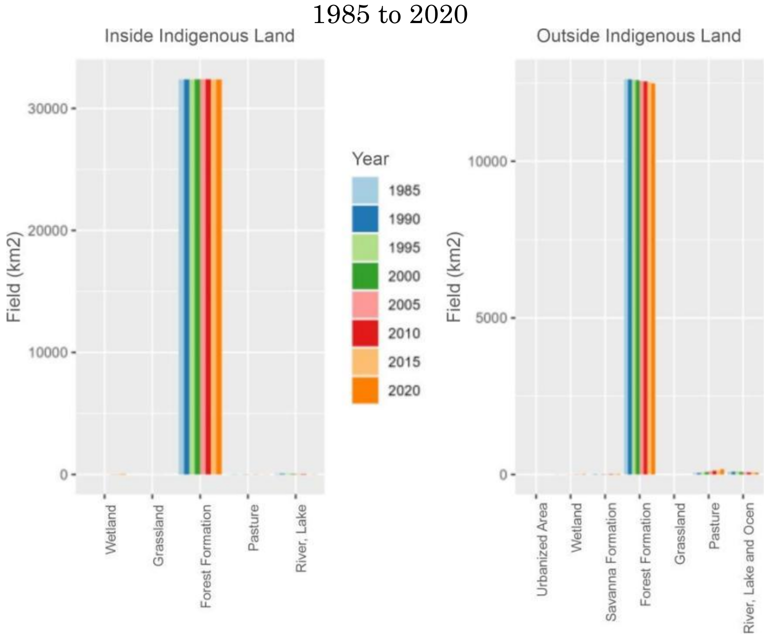
Polygons 1 and 6 are located in the western Amazon state (Figure 2), and polygon 7 is located in the northwestern Pará. Surrounding hexagons 1, 6, and 7, there are blocks of Indigenous lands extending around and some nearby UCs (Figure 2). According to Montagna *et al.* (2012), UCs are important tools for environmental conservation worldwide. The UCs have a buffer zone (ZA), which preserves the UC and ZA itself, although these polygons do not border them. This explains the results shown in Figures 2 to 7. Throughout 1985 and 2020, forest formation remained preserved inside and outside Indigenous lands in the polygons.

Figure 2 - Land use and land cover inside and outside Indigenous lands in polygon 1



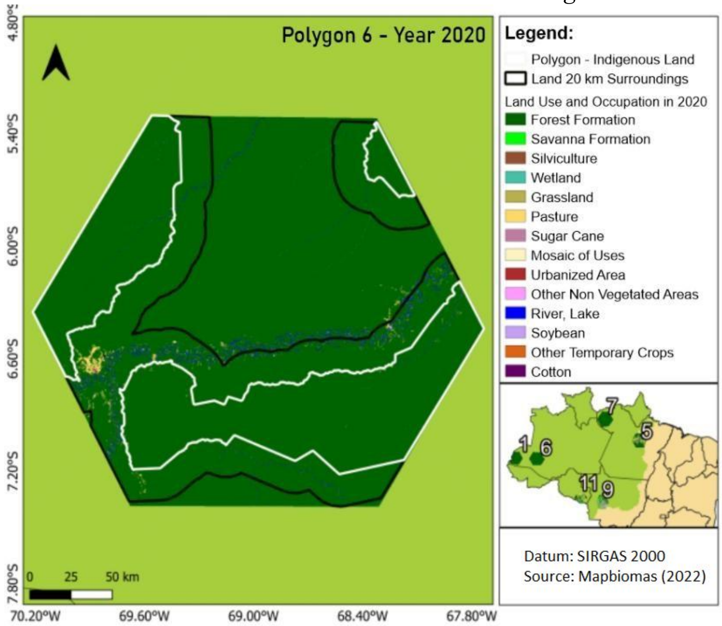
Source: The authors (2024).

Figure 3 - Land use and land cover inside and outside Indigenous lands in polygon 1, in km², from 1985 to 2020



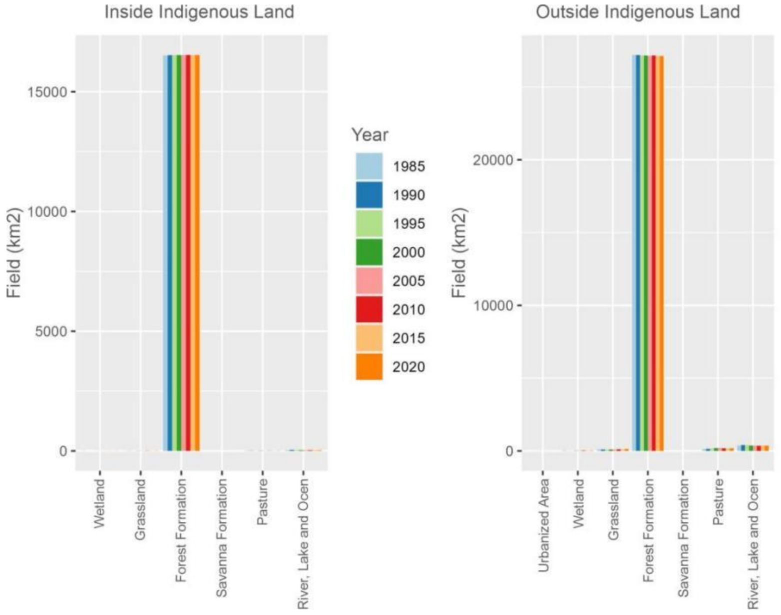
Source: The authors (2024).

Figure 4- Land use and land cover inside and outside Indigenous lands in polygon 6



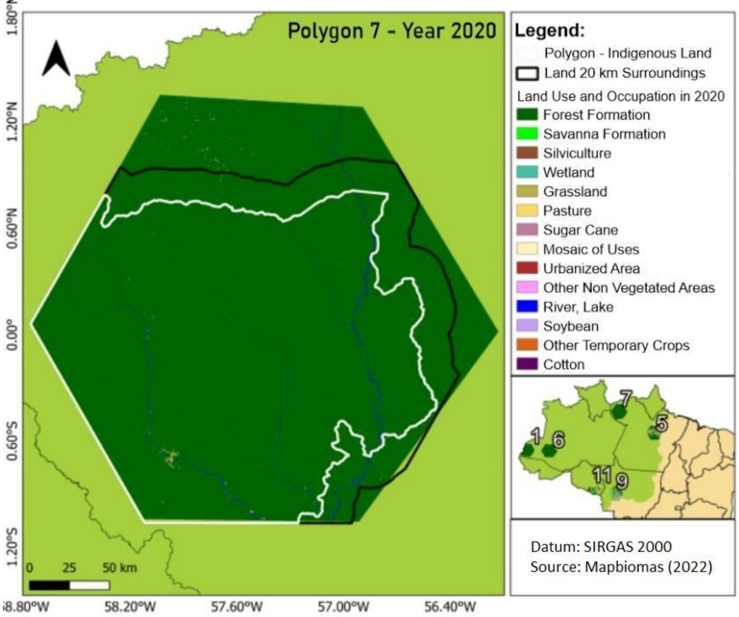
Source: The authors (2024).

Figure 5 - Land use and land cover inside and outside Indigenous lands in polygon 6, in km², from 1985 to 2020



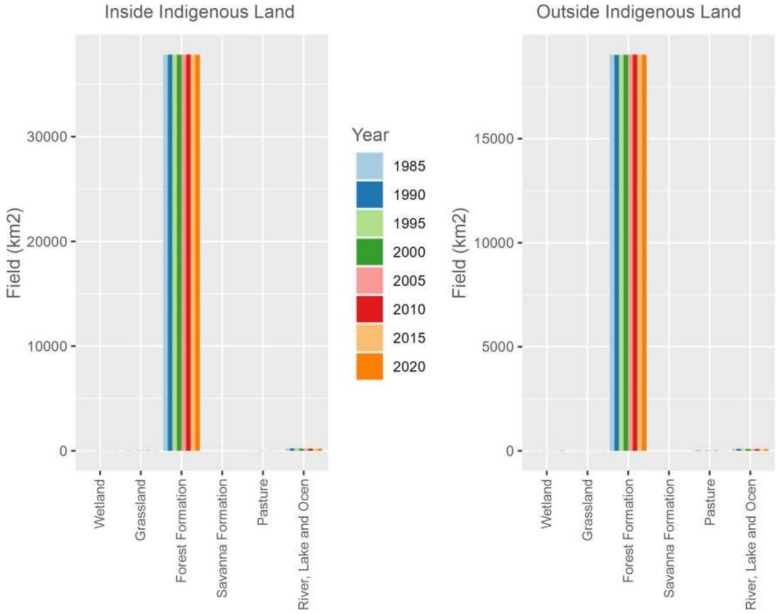
Source: The authors (2024).

Figure 6 - Land use and land cover inside and outside Indigenous lands in polygon 7



Source: The authors (2024).

Figure 7 - Land use and land cover inside and outside Indigenous lands in polygon 7, in km², from 1985 to 2020



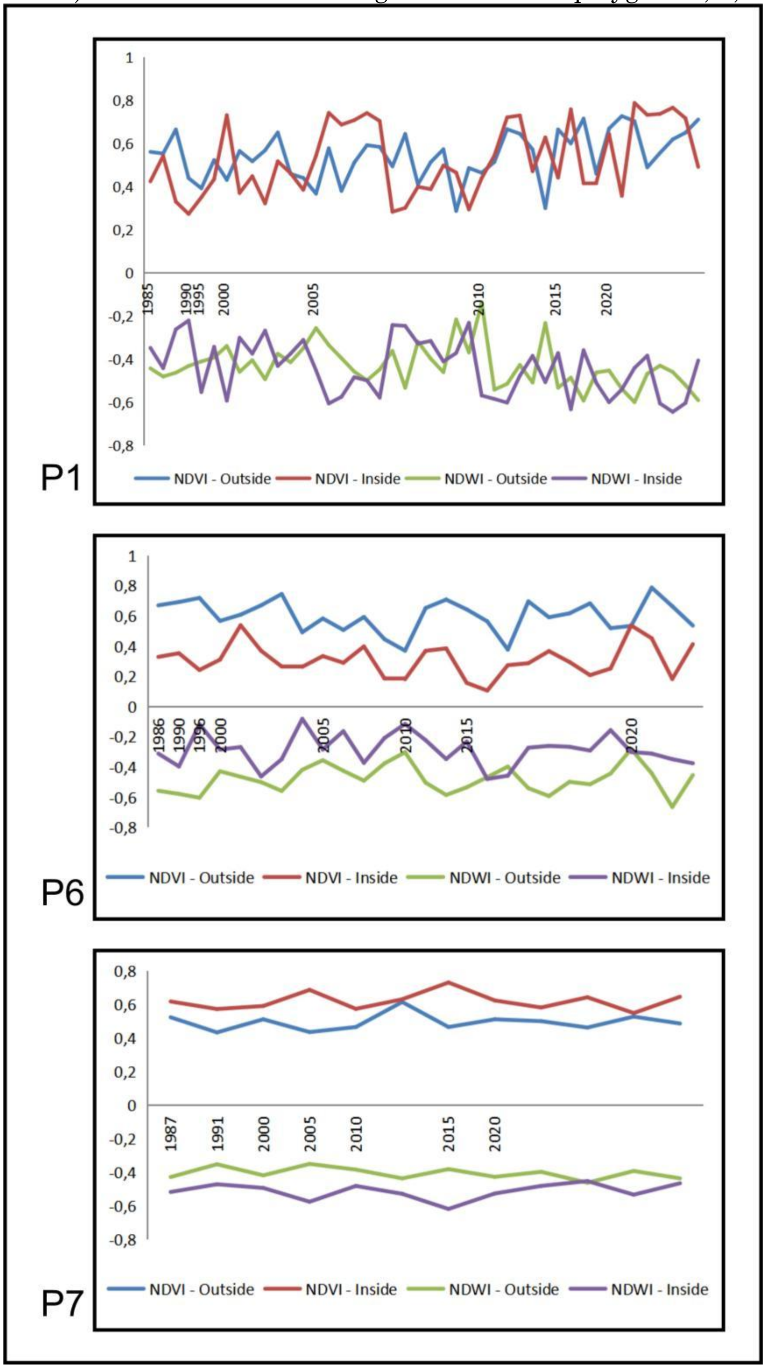
Source: The authors (2024).

NDVI and NDWI of polygons 1, 6, and 7

Conservation of native vegetation influences NDVI and NDWI results. Vegetation areas preserved showed healthy and moderate healthy vegetation (Figure 8 and Table 2). In polygon 1, the region inside Indigenous lands varied from 0.3 to 0.8, while outside Indigenous lands ranged from 0.3 to 0.7. According to Xavier and Fortes (2023), this indicates the presence and conservation of dense vegetation and water availability. In polygon 6, the region inside Indigenous lands varied from 0.1 to 0.5, and outside Indigenous lands ranged from 0.4 to 0.7, indicating healthy vegetation. However, NDVI inside Indigenous lands was lower than outside Indigenous lands. This is because a river crosses the 20-km buffer zone (Figure 4), while there are no water bodies inside Indigenous lands, and water is essential for vegetation development. In polygon 7, the region inside Indigenous lands varied from 0.6 to 0.8, and outside Indigenous lands ranged from 0.4 to 0.6, indicating very and moderate healthy vegetation, respectively. The indexes presented lower fluctuation over the years since there are fewer pasture areas (Figures 6 and 7) than the other polygons and their surroundings, which maintain vegetation health and soil moisture. All polygons and their surroundings remained preserved, despite presenting small differences.

Vegetation needs an appropriate amount of water and sunlight to be and remain healthy. The NDWI showed similar variation between polygons and their surroundings (Figure 8). Polygon 1 varied from -0.6 to -0.2, polygon 6 from -0.6 to -0.1, and polygon 7 from -0.6 to -0.3. The lack of changes in the indexes indicates that the forest remained in good quality over the years.

Figure 8 - Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) inside and outside Indigenous lands in polygons 1, 6, and 7



Source: The authors (2024).

LST of polygons 1, 6, and 7

According to Webler *et al*. (2013), the LST in forest regions is mild compared to pasture areas since the soil is not exposed and is protected by deep roots. Average LST in the study areas (polygons 1, 6, and 7), which correspond to forest conservation, are presented in Table 3. The average LST was calculated in 2000 and 2020 for each polygon and its surroundings. The average values are calculated starting from the year 2000 because some polygons did not present recorded data in previous years.

The average LST in polygon 1 did not vary inside and outside Indigenous lands between 2000 and 2020. In polygon 6, LST recorded 3 °C higher than its surroundings, explaining the vegetation with deficiencies in NDVI. The higher temperature in the polygon than in its surrounding area of 20 km leads to vegetation becoming dry, and there is a lack of water bodies in this polygon to lower the soil temperature (Figure 4). In polygon 7, LST presented 2 °C lower than its surroundings in 2020, which had a higher concentration of water bodies.

Table 3 - Average Land Surface Temperature (°C)

	Outside Indigenous lands		Inside Indigenous lands	
Polygon	2000	2020	2000	2020
P1	19.47	19.09	22.22	22.19
P6	18.63	18.1	21.98	25.8
P7	22.25	22.22	22	18.04

Source: The authors (2024).

Polygons 5, 9, and 11

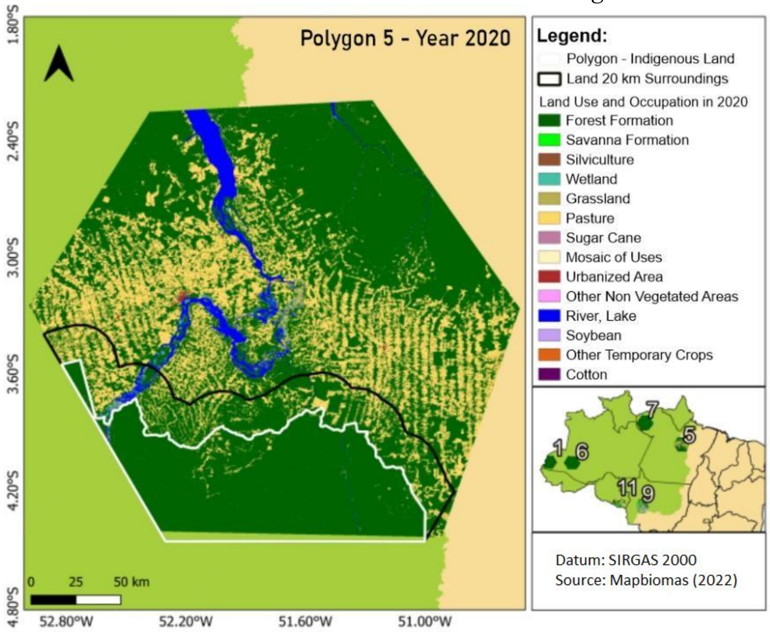
Polygons 5, 9, and 11 are near the transition zone between the Amazon and Cerrado biomes (Figure 1). Domingues and Bermann (2012) explained that the advance of agriculture and livestock in Brazil spread from the southern region and gradually expanded to the northern region, devastating the Amazon Rainforest. This fact appears in the results of the polygons.

Land use and land cover of polygons 5, 9, and 11

Polygon 5 is located in central Pará and polygon 11 is in southern Rondônia (Figure 1). There is a block of Indigenous lands and some UCs surrounding hexagons 5 and 11. Even though these polygons are in an area that may be impacted by agriculture and livestock, they remained preserved over the years (Figures 9 to 14). Forest formation inside Indigenous lands in both polygons did not significantly change, while part of the forest has been replaced by pasture outside Indigenous lands. Polygon 9 is located in southeastern Pará and northeastern Mato Grosso (Figure 1). Agriculture and livestock areas have occupied a larger portion of the forest. Inside Indigenous lands in the polygon 9, the vegetation with forest, savanna, and grassland formations remained relatively preserved. However, regions outside Indigenous lands became pasture, temporary croplands, and, primarily, soybean cultivation (Figures 11 and 12).

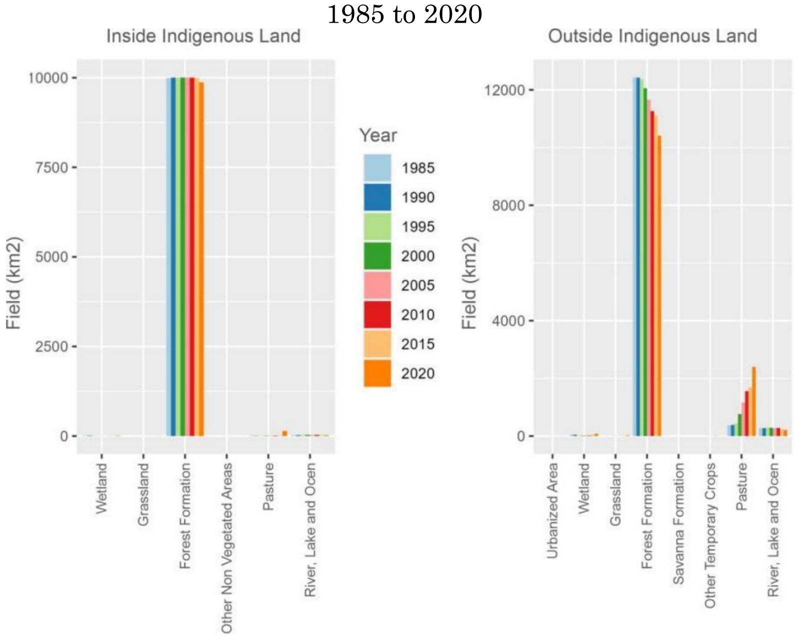
Lima and Mendes (2015) explained that Indigenous lands became resilient islands exposed to the negative effects of the land use patterns in surrounding areas. This is because the region inside polygons, Indigenous lands, managed to maintain conservation while outside Indigenous lands were occupied by agriculture and livestock. Indigenous lands near UCs can preserve their lands even more effectively, as shown in polygons 5 and 11 (Figures 1, 9, 10, 13, and 14). According to Walker *et al.* (2020), Indigenous peoples, traditional communities, and UCs have prevented deforestation and greenhouse gas emissions for decades. However, these areas have become more vulnerable due to degradation processes and forest disturbance. They also stated that eliminating this threat is essential to the future of the Amazon Rainforest, which ensures the stability of the global environmental balance and the vast biodiversity.

Figure 9 - Land use and land cover inside and outside Indigenous lands in polygon 5



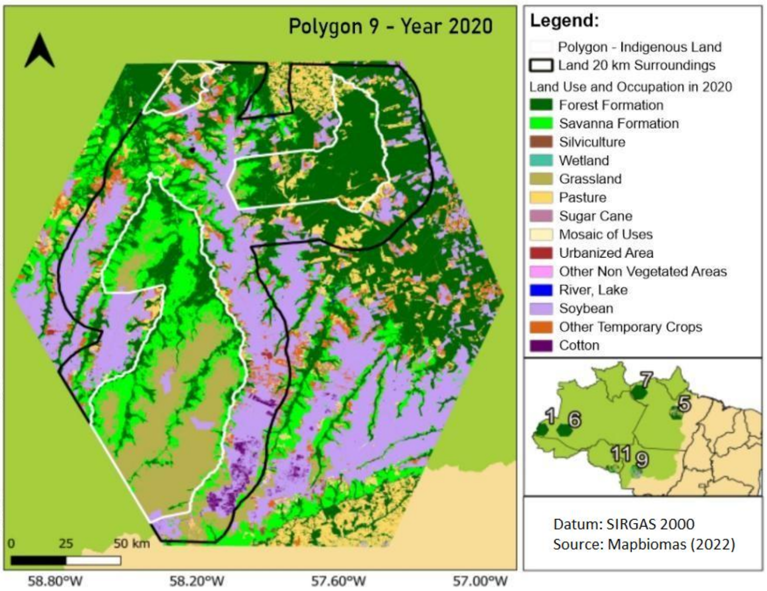
Source: The authors (2024).

Figure 10 - Land use and land cover inside and outside Indigenous lands in polygon 5, in km², from 1985 to 2020



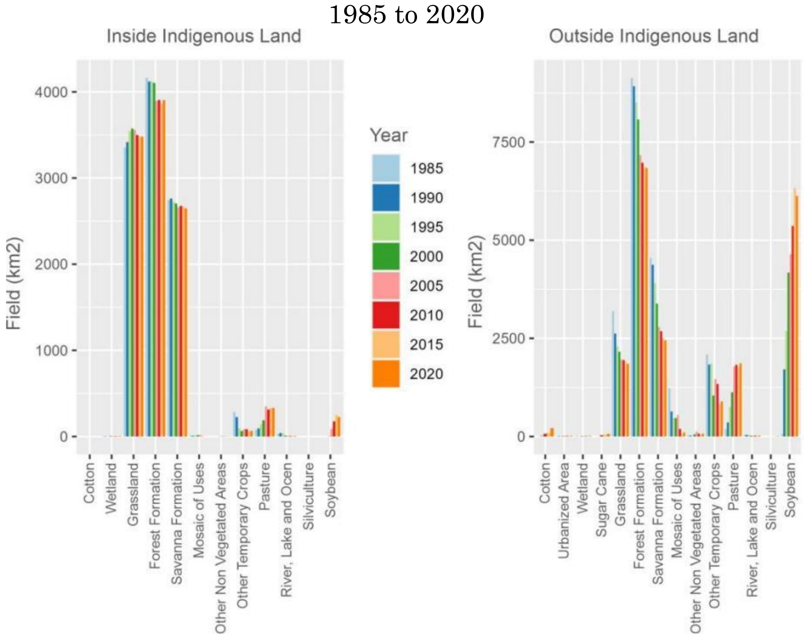
Source: The authors (2024).

Figure 11 - Land use and land cover inside and outside Indigenous lands in polygon 9



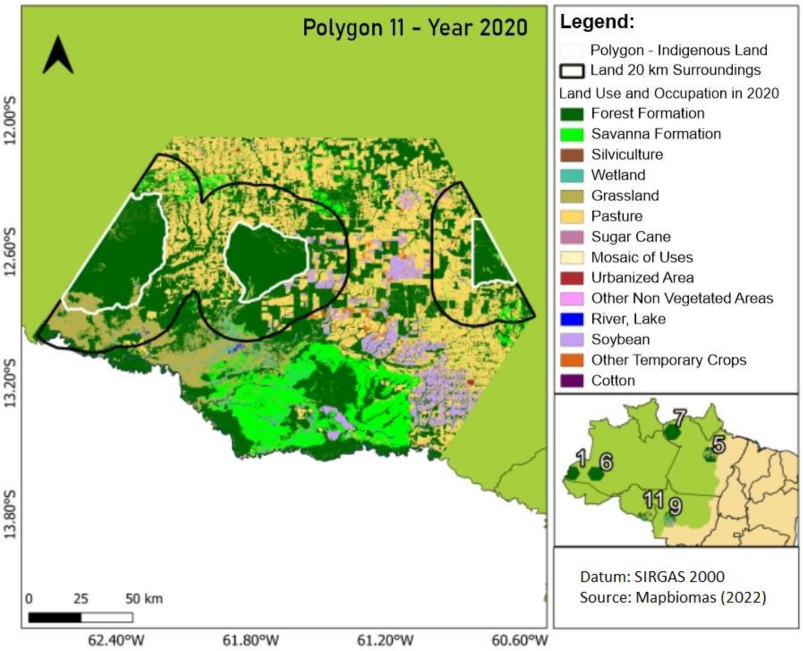
Source: The authors (2024).

Figure 12 - Land use and land cover inside and outside Indigenous lands in polygon 9, in km², from 1985 to 2020



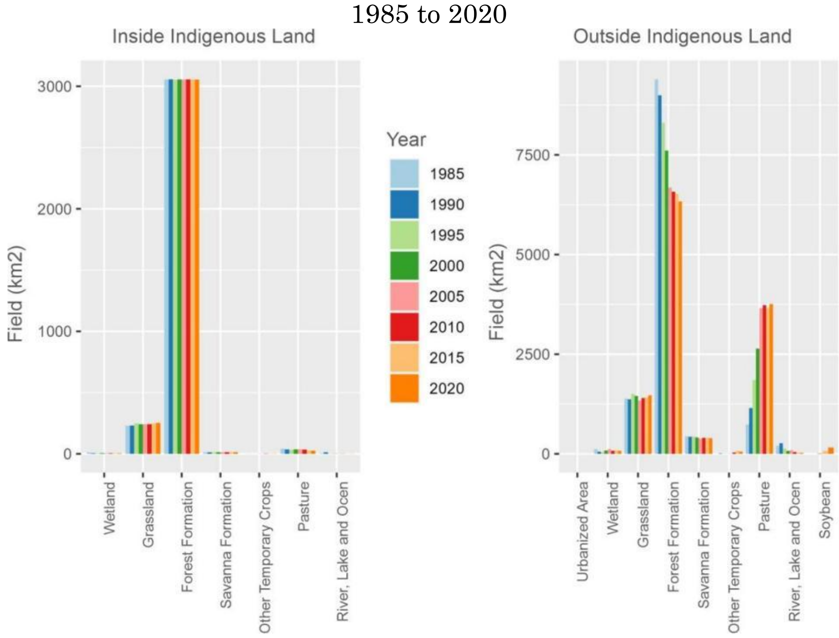
Source: The authors (2024).

Figure 13 - Land use and land cover inside and outside Indigenous lands in polygon 11



Source: The authors (2024).

Figure 14 - Land use and land cover inside and outside Indigenous lands in polygon 11, in km², from 1985 to 2020



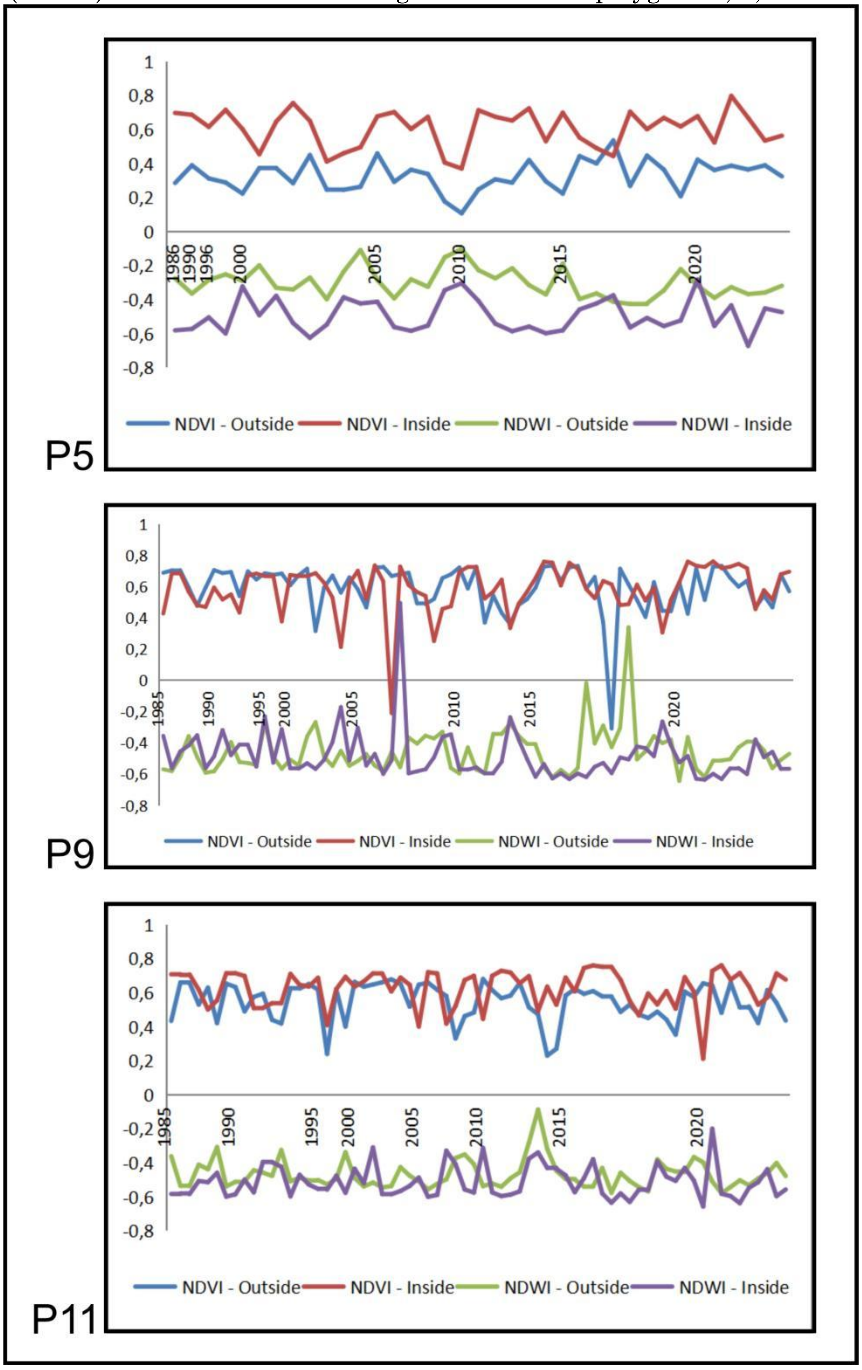
Source: The authors (2024).

NDVI and NDWI of polygons 5, 9, and 11

In polygon 5, the NDVI inside Indigenous lands indicated healthy vegetation (0.4 - 0.8), and the NDVI outside Indigenous lands indicated predominantly unhealthy vegetation (0.1 - 0.4) since forest inside Indigenous lands was preserved, and its surroundings were replaced by pasture areas (Figures 9, 10, and 15 and Table 2). In polygon 9, where land use and land cover significantly changed, the NDVI inside and outside Indigenous lands strongly varied. In 2005, NDVI inside Indigenous lands was -0.2, and, in 2015, NDVI outside Indigenous lands was -0.3. These values indicate areas with no vegetation (Figure 15 and Table 2). In polygon 11, the NDVI inside and outside Indigenous lands varied from 0.3 to 0.7, indicating healthy vegetation (Figure 15 and Table 2). The region inside Indigenous lands maintained forest conservation. Although the same did not occur outside Indigenous lands (Figures 13 and 14), NDVI values were high. According to Andrade *et al*. (2014), pasture management and spatial-temporal heterogeneity of precipitation over the years may influence these results.

The NDWI in polygons 5, 9, and 11 showed low soil moisture in the vegetation areas (Figure 15 and Table 2). However, only polygon 9 showed flooded areas (water surface). There were two records, one inside Indigenous lands in 2005 and another outside Indigenous lands in 2015. In these same years and respective regions, the NDVI indicated areas with no vegetation. Vegetation coverage regulates water flow in a river basin (Harris *et al*., 2006). Lack of vegetation prevents rainwater absorption, causing flooding and soil erosion.

Figure 15 - Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) inside and outside Indigenous lands in polygons 5, 9, and 11



Source: The authors (2024).

LST of polygons 5, 9, and 11

Ribeiro (1993) stated that deforestation impacts radiation flux and water balance in the Amazon region. The author mentioned the study conducted by Nobre *et al.* (1989), who claimed that the LST in a deforested area in the Amazon region increased from 1 to 3 °C. Considering polygons 1, 6, and 7 and their surroundings, in which the forest is preserved inside and outside Indigenous lands, the average LST did not change over the years. In contrast, polygons 5, 9, and 11, in which their surroundings changed by agriculture and livestock activities, reported an increase in the average LST of their surroundings (Table 4).

Table 4 - Average Land Surface Temperature (°C)

	Outside Indigenous lands		Inside Indigenous lands	
Polygon	2000	2020	2000	2020
P5	20.74	26.96	18.45	18.07
P9	19.09	No record	20.53	No record
P11	20.12	26.18	19.95	20.66

Source: The authors (2024).

FINAL CONSIDERATIONS

Indigenous lands play a key role in the Amazon conservation. Analyzing polygons near UCs and agriculture and livestock areas, this study showed that UCs strongly contributed to preserving vegetation, temperature, and soil moisture within Indigenous lands. In contrast, expanding agriculture and livestock areas near Indigenous lands significantly changed vegetation, temperature, and soil moisture.

The NDVI, NDWI, and LST analysis showed that polygons near UCs presented higher environmental stability than polygons adjacent to agriculture and livestock areas. This difference highlights the importance of UCs as natural barriers to the growth of agricultural activities and environmental degradation.

Despite the clear contribution of Indigenous lands to the Amazon conservation, the importance of these lands and Indigenous peoples is still underestimated. Future research may analyze the impacts of deforestation on Indigenous lands using other indexes, such as the Normalized Difference Drought Index (NDDI) and Normalized Difference Built-up Index (NDBI). Applying these indexes to all blocks of Indigenous lands will enable a deeper understanding of environmental dynamics and challenges faced by these territories.

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