




## Article

# Land Use Change and Its Climatic and Vegetation Impacts in the Brazilian Amazon

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## Abstract

The Brazilian Amazon is recognized worldwide for its biodiversity and it plays a key role in maintaining the regional and global climate balance. However, it has recently been greatly impacted by changes in land use, such as replacing native forests with agricultural activities. These changes have resulted in serious environmental consequences, including significant alterations to climate and hydrological cycles. This study aims to analyze changes in land use and land covered in the Brazilian Amazon between 2001 and 2023, as well as the resulting effects on precipitation variability, land surface temperature, and evapotranspiration. Data obtained via remote sensing and processed on the Google Earth Engine platform were used, including MODIS, CHIRPS, Hansen products. The results revealed significant changes: forest formation decreased by 8.55%, while agricultural land increased by 575%. Between 2016 and 2023, accumulated deforestation reached 242,689 km<sup>2</sup>. Precipitation decreased, reaching minimums of 772.7 mm in 2015 and 726.4 mm in 2020. Evapotranspiration was concentrated between 941 and 1360 mm in 2020, and surface temperatures ranged between 30 °C and 34 °C in 2015, 2020, and 2023. We conclude that anthropogenic transformations in the Brazilian Amazon directly impact vegetation cover and the regional climate. Therefore, conservation and monitoring measures are essential for mitigating these effects.



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**Keywords:** forest degradation; deforestation; forest fires; rainfall; remote sensing

## 1. Introduction

The Brazilian Amazon is notable for its size and the ecosystem services it provides, such as carbon storage. These services influence the regional and global climate. However, deforestation for agricultural expansion endangers this ecosystem, resulting in biodiversity loss and alterations to the hydrological cycle.

The Amazon is the world's largest continuous tropical forest, representing about 35% of the remaining primary forests and covering 3% of the Earth's surface. Home to significant biodiversity, the forest provides important ecosystem services, such as regulating hydrological and climatic cycles and influencing the climate on a regional and global scale [1–3].

The Amazon rainforest is notable not only for its vast size and climatic importance, but also for having the greatest concentration of biodiversity in tropical forests. It houses over 20% of known terrestrial species. It is estimated that this biome contains around 45 thousand

species of plants and vertebrates, including approximately 14 thousand species of seed plants, nearly half of which are identified trees [4,5].

In addition to its vast biodiversity, the Brazilian Amazon influences the regional and global climate due to its hot, humid tropical climate. Vegetation plays a crucial role in regulating atmospheric humidity and transporting precipitation, water vapor, aerosols, and gases to other regions of Brazil. The region accounts for about 71% of Brazil's river flow, corresponding to 36.6% of South America's total and 8% of the global total. The region is also responsible for about 13% of surface runoff into the oceans, which highlights its importance in maintaining biodiversity and balancing the global water and carbon cycles [6–8].

The Brazilian Amazon is still considered a continuous natural ecosystem with relatively low levels of habitat fragmentation and isolation. However, its ecological integrity is increasingly threatened. The main drivers of degradation include the expansion of agribusiness, particularly extensive livestock farming and large-scale soybean production; growth in legal and illegal mining; exploitation of energy resources; construction of hydroelectric plants; development of highways; and unplanned settlements resulting from colonization policies [9–14].

Changes in land use and land cover in the Amazon, primarily driven by the expansion of livestock pastures and mechanized agriculture, have resulted in significant greenhouse gas (GHG) emissions [15]. Deforestation and burning release large amounts of carbon dioxide (CO<sub>2</sub>), and cattle ranching contributes significantly to methane (CH<sub>4</sub>) emissions, which is one of the main GHGs with high global warming potential [16,17]. These transformations compromise the Amazon's role as a climate regulator, alter the hydrological regime, intensify drought periods, and increase the frequency of extreme events [18].

Human actions in the Brazilian Amazon have profound and interconnected impacts. For instance, removing vegetation increases erosion and siltation in rivers and streams, which degrades the quality and dynamics of aquatic ecosystems. Furthermore, environmental degradation directly endangers biodiversity and the resilience of ecosystems by reducing habitat availability, altering the relationships between species, and degrading the services those ecosystems provide to maintain life [19–21].

Changes in land use and land cover, particularly the replacement of forests with agricultural activities and other uses, profoundly impact the hydrological cycle [22]. These changes result in greater surface runoff, reduced groundwater recharge, and altered precipitation patterns, including a delayed rainy season onset and reduced total precipitation. Furthermore, the loss of forest cover increases surface temperatures, thereby intensifying the effects of climate change [23–28].

Furthermore, this environment has been affected by increasingly frequent and extreme droughts, which will likely have a negative impact on the equilibrium of humid tropical forests in the coming decades. Often associated with climate anomalies on regional and global scales, such as El Niño, these events have caused significant reductions in water availability, which directly affects vegetation dynamics and ecosystem processes [29,30].

Efficient environmental monitoring methods are becoming essential given the mounting pressure on Brazilian Amazon ecosystems, which is characterized by deforestation and agricultural expansion. Developing and applying techniques that combine affordability, speed, and accuracy in processing large amounts of spatial data is crucial for supporting territorial control and planning activities [31,32].

In this scenario, geographic information systems (GISs) and other technological tools play a strategic role in analyzing the factors that drive environmental changes in the Brazilian Amazon. GISs integrate and cross-reference spatial and temporal data, enabling the detailed monitoring of landscape dynamics [33]. They allow for the systematic mapping and analysis of variations in parameters such as precipitation, surface soil temperature, and

vegetation cover over time. These capabilities provide support for identifying vulnerable areas, territorial planning, and formulating strategies aimed at mitigating environmental degradation.

In the context of the Brazilian Amazon, it is crucial to understand the relationship between changes in land use and land cover, as well as their impact on climate variables such as precipitation, evapotranspiration, and land surface temperature. Deforestation intensification and its spatial and temporal trends directly influence the region's water and energy balance, disrupting natural cycles and contributing to the degradation of biological and water resources [34,35].

Investigating the correlation between these changes and climate factors is essential for supporting conservation strategies and the sustainable management of the Brazilian Amazon. We hypothesize that changes in land use and land cover in the region have caused significant changes in precipitation patterns, increased surface temperature, and reduced evapotranspiration.

In this context, our objective was to analyze the transformations in land use and land cover in the Brazilian Amazon over a 23-year period, as well as their effects on precipitation variability, surface temperature, and evapotranspiration, in order to understand the interactions between anthropogenic changes and environmental processes in this biome.

## 2. Materials and Methods

### 2.1. Study Area

The study area encompasses the Brazilian Amazon (Figure 1), recognized as the largest biome in Brazil. Spanning approximately 4.2 million km<sup>2</sup>, it accounts for about 49% of the country's territory and is distributed across nine federative units: Amazonas, Pará, Mato Grosso, Acre, Rondônia, and Roraima, as well as parts of Tocantins and Maranhão [36].

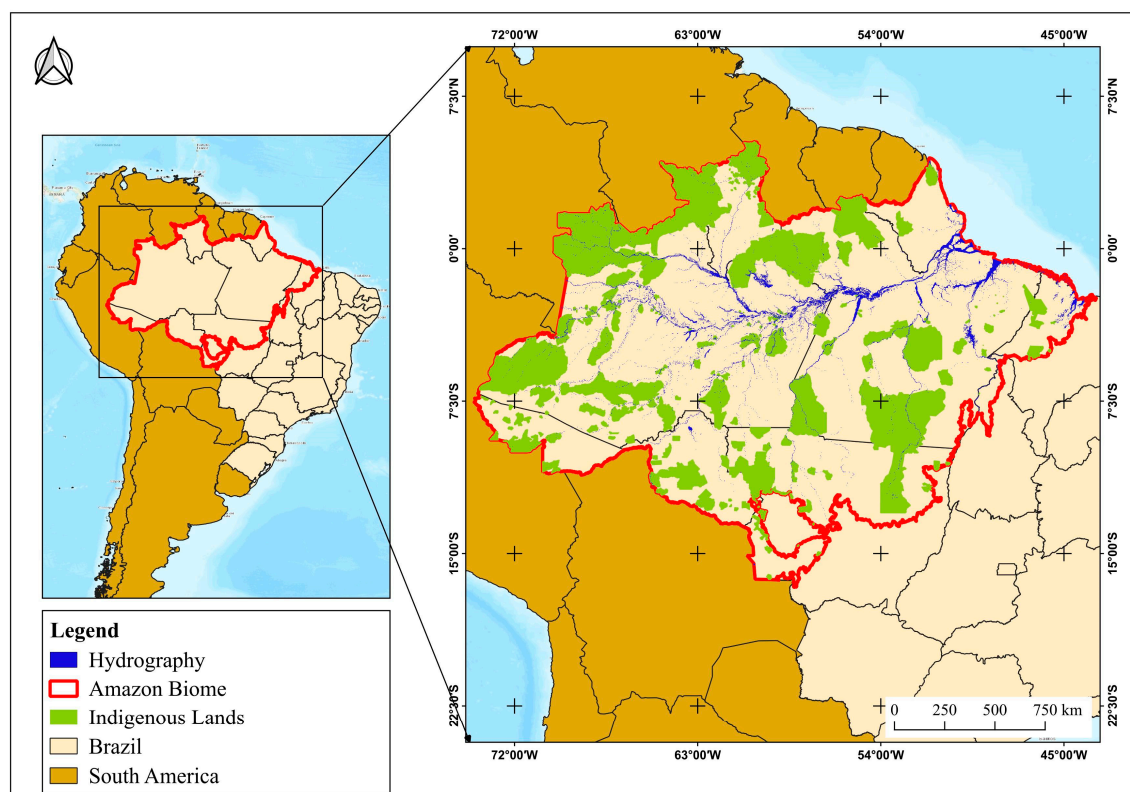


Figure 1. Delimitation of the area corresponding to the Brazilian Amazon.

The predominant vegetation is dense, evergreen, broadleaf rainforest, which exhibits different physiognomies associated with the local water regime. Standout types include permanently flooded igapó forests, floodplain forests subject to periodic flooding (subdivided into low and high floodplains), and dryland forests in higher, flood-free areas [37,38]. Deciduous and semi-deciduous forests are also present, particularly where the Brazilian Amazon transitions to the Cerrado biome [39].

The most geographically extensive soils in the Brazilian Amazon are Ferralsols and Acrisols [40]. According to the Köppen classification, the dominant climate types in the Brazilian Amazon are Humid Equatorial (Af), Tropical Monsoon (Am), and Tropical with a Dry Season in Winter (Aw) [41].

## 2.2. Land Use and Land Cover Change (LULCC)

We based our analysis of Land Use and Land Cover Change (LULCC) on MapBiomas Project Collection 9.0 data from the Annual Series of Land Use and Cover Maps of Brazil. This dataset provides national-scale satellite image classification information [42]. With a spatial resolution of 30 m, we selected the years of 2001, 2008, 2015, and 2023.

We generated the images using machine learning algorithms on the Google Earth Engine (GEE) platform from automated data processing from the Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS) sensors.

The overall accuracy of Collection 9.0 was 96.80% for the Brazilian Amazon. The allocation disagreement rate was 2.25%, and the quantity disagreement rate was 0.95%. We reclassified the LULCC data from 29 to 11 classes for each analyzed year. The converted classes and their respective original attributes are as follows: (1) forest formation, (2) savanna formation, (3) pasture, (4) agriculture (temporary and perennial crops), (5) flooded forests, (6) wetlands, (7) fields, (8) mangroves, (9) mining, (10) urbanization, and (11) rivers and lakes.

We accessed images from the selected years and exported them from the GEE platform. We then performed the final processing and extraction of information from the study area using QGIS software (version 3.34.14) [43]. We used the biome sections as a mask for spatial delimitation. Temporal analyses identified and quantified changes in LULCC classes during the analyzed period.

## 2.3. Vegetation Analysis Using the Normalized Difference Vegetation Index (NDVI)

We analyzed vegetation dynamics in the Brazilian Amazon using version 6.1 of the MOD13A1 product on the GEE platform, which provides the Normalized Difference Vegetation Index (NDVI). This product offers 16-day composites with a spatial resolution of 500 m derived from Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on the Terra satellite [44].

We selected images from 2001, 2008, 2015, and 2023, prioritizing periods with less cloud cover that generally corresponded to the region's dry season. To ensure data quality, we applied the "SummaryQA" layer filter, considering only pixels with quality values between 0 and 1 [45]. Annual average composites were generated from the available images for each year. Pixels with missing data or compromised by cloud cover were automatically discarded during the filtering process and excluded from the temporal average calculation.

## 2.4. Space Climate Monitoring: Precipitation and Land Surface Temperature (LST) from 2001 to 2023

We analyzed climate variability in the Brazilian Amazon from 2001 to 2023 using precipitation and land surface temperature (LST) data. We obtained precipitation estimates from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset.

This dataset combines satellite observations and surface precipitation data, providing a consistent time series with a spatial resolution of  $0.05^\circ$  ( $\sim 5$  km) [46]. We extracted and processed the data using the GEE platform.

We obtained LST data from the MODIS sensors aboard the Terra and Aqua satellites using MOD11A1 and MYD11A1 products. These products provide daily estimates with a spatial resolution of 1 km [47]. The images were fully processed and analyzed in the GEE platform.

Filtering based on the quality layer (“QC\_Day”) excluded pixels with low reliability, considering only those with acceptable quality levels according to the official product documentation. The temperature values, originally in Kelvin, were converted to degrees Celsius [48]. To illustrate the thermal variability of the Earth’s surface from 2001 to 2023, annual average composites were generated. Pixels with missing or compromised data were automatically removed during the compositing process.

### 2.5. Estimating Evapotranspiration (ET) with the MOD16 Product

We estimated evapotranspiration (ET) in the Brazilian Amazon using the MOD16A2 product obtained from the GEE platform. Derived from MODIS sensor data from the Terra and Aqua satellites, this product provides estimates of actual and potential ET and latent heat flux with spatial and temporal resolutions of  $1 \text{ km}^2$  and eight days, respectively. These resolutions allow for monthly and annual aggregations [49,50].

The MOD16 algorithm is based on the Penman–Monteith equation, which has been adapted for remote sensing according to a model developed by Cleugh et al. [51]. Estimated ET uses biophysical variables derived from other MODIS products, including land cover (MCD12Q1), the vegetation index (MOD13Q1), the leaf area index (LAI/FPAR, MOD15A2H), and albedo (MOD43C1). The Global Modeling and Assimilation Office (GMAO) provides the necessary meteorological data, including incident solar radiation, mean and minimum air temperature, and water vapor pressure. The GMAO model has a spatial resolution of  $1.00^\circ \times 1.25^\circ$ .

In GEE, we selected MOD16A2 images from 2001 to 2023 and restricted them to the geographic extent of the Brazilian Amazon. We converted the ET values, originally on an eight-day scale with units of  $\text{kg m}^{-2} \text{ day}^{-1}$ , to millimeters (mm) and aggregated them into annual averages [52]. Only pixels with valid values were considered. Those with missing data or low quality according to the “ET\_QC” layer were discarded.

We exported the processed data from GEE as a GeoTIFF raster and imported it into QGIS. There, we cropped the data based on the Brazilian Amazon boundary. Then, we performed visual analyses and created annual thematic maps using QGIS [53].

### 2.6. Quantifying Deforestation and Fires Using Remote Sensing Data

We used the Hansen Global Forest Change (HGFC) product, developed by Hansen et al. [54], to quantify the deforested area in the Brazilian Amazon. HGFC provides time series data on forest cover loss and gain based on Landsat satellite images on a global scale. We accessed and processed the data through the GEE platform using JavaScript.

We conducted our analysis from 2001 to 2023 and organized the results into three time intervals: 2001–2008, 2009–2015, and 2016–2023. This approach allowed us to identify spatial and temporal patterns of deforestation in the biome over the last two decades and support our analysis of trends in native vegetation loss.

We used the MODIS Burned Area product (MODIS/061/MCD64A1) to analyze forest fires. This product provides monthly data on burned areas based on fire scar detection, with a spatial resolution of 500 m [55]. Using the GEE platform, we processed the data

and generated maps to quantify the extent of areas affected by forest fires during the same period (2001–2023).

### 2.7. Mann–Kendall Test and Correlation Test

Trend analysis was performed using the Mann–Kendall (MK) test, a nonparametric statistical method commonly used to detect monotonic trends in environmental time series [56]. The MK test was chosen for its ability to handle data that does not follow a normal distribution, which is common in series derived from remote sensing. It is also less sensitive to extreme values and missing data [57,58]. The MK test was applied pixel by pixel to annual data on NDVI, LST, precipitation, and ET from 2001 to 2023. This allowed for the identification of spatially explicit positive or negative trends over time. Values of the MK statistic range from  $-1$  to  $1$ . Negative values indicate a decreasing trend, positive values indicate an increasing trend, and values close to zero indicate an absence of a significant trend [59]. The MK test is suitable for large-scale spatial and temporal investigations, such as the present study, when the objective is to identify general patterns of change and support regional environmental diagnoses.

In addition to trend analysis, we performed a spatial correlation analysis on the NDVI, LST, and precipitation indicators. We used Pearson’s correlation coefficient to measure the degree of association between these variables. The values of the coefficient vary between  $-1$  and  $1$ :  $-1$  indicates a perfect negative correlation,  $0$  indicates no correlation, and  $1$  indicates a perfect positive correlation [60].

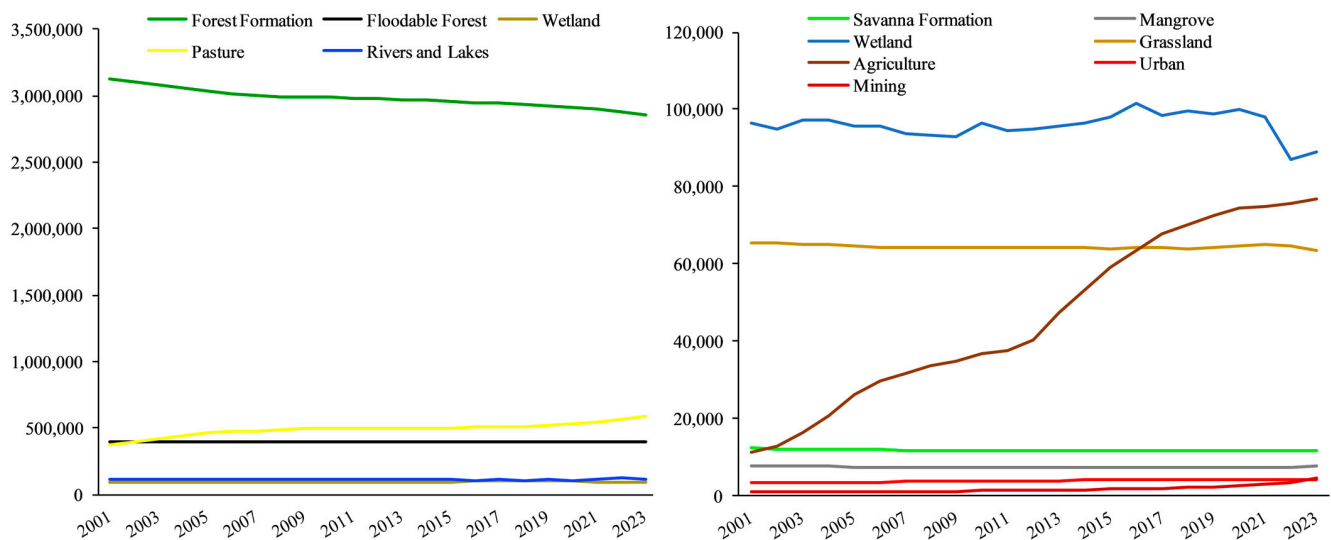
We conducted all statistical analyses using R software (version 4.2.2) [61]. We exported the results of the MK test and correlations in raster and vector formats and organized them into thematic maps in QGIS to better interpret the spatial trends and associations between the analyzed environmental variables.

## 3. Results and Discussion

Between 2001 and 2023, significant changes occurred in LULCC in the Brazilian Amazon (Table 1 and Figure 2). The forest formation, which represents the largest portion of the region, shrank from approximately  $3,125,794.39 \text{ km}^2$  to  $2,858,403.69 \text{ km}^2$ . The floodable forest area remained relatively stable, fluctuating slightly around  $392,669.02 \text{ km}^2$ . The wetland class showed subtle fluctuations, remaining close to  $89,011.72 \text{ km}^2$ , while the rivers and lakes category remained at approximately  $115,970.19 \text{ km}^2$ .

**Table 1.** Variation in Land Use and Land Cover Classes in (LULCC) the Brazilian Amazon between 2001 and 2023.

Land Use and Land Cover Classes	2001		2023		Percent Variation Between 2001 and 2023
	km <sup>2</sup>	%	km <sup>2</sup>	%	
Forest Formation	3,125,794.39	74.15	2,858,403.69	67.81	−8.55
Savanna Formation	12,339.88	0.29	11,596.73	0.28	−6.02
Mangrove	7592.69	0.18	7587.29	0.18	−0.07
Floodable Forest	400,338.24	9.50	392,669.02	9.32	−1.92
Wetland	96,444.52	2.29	89,011.72	2.11	−7.71
Grassland	65,425.23	1.55	63,439.88	1.50	−3.03
Pasture	380,130.66	9.02	590,712.43	14.01	55.40
Agriculture	11,374.69	0.27	76,819.99	1.82	575.36
Urban	3407.29	0.08	4442.65	0.11	30.39
Mining	1019.77	0.02	4769.56	0.11	367.71
Rivers and Lakes	111,555.80	2.65	115,970.19	2.75	3.96



**Figure 2.** Variation in Land Use and Land Cover Classes (LULCC) in kilometers squared in the Brazilian Amazon between 2001 and 2023.

Pasture grew continuously, expanding from around 380,130.66 km<sup>2</sup> in 2001 to 590,712.43 km<sup>2</sup> in 2023, a 55.40% increase, reflecting the conversion of natural areas for agricultural use. Agricultural area expanded significantly, growing from 11,374.69 km<sup>2</sup> to 76,819.99 km<sup>2</sup>—an increase of 575%. Meanwhile, the savanna formation remained relatively unchanged, oscillating around 1,000,000 km<sup>2</sup>.

Despite its smaller area, mining expanded notably in the Amazon, increasing from 1019.77 km<sup>2</sup> in 2001 to 4769.56 km<sup>2</sup> in 2023—a growth of about 367.71%. Meanwhile, mangroves remained practically constant, maintaining coverage close to 15,000 km<sup>2</sup>. Despite occupying a smaller area, urban areas exhibited a slight growth trend, expanding from 3407.29 km<sup>2</sup> to around 4442.65 km<sup>2</sup>, a 30% increase, in line with population growth and regional infrastructure expansion.

As shown in Figure 2, the dynamics of LULCC revealed a significant anthropogenic influence, including a notable decrease in forest formation and an increase in areas designated for pasture and agriculture. Similarly, Cabral et al. [62] identified high rates of forest loss over decades associated with fragmentation and land use conversion in protected areas of the Brazilian Amazon using remote sensing data.

According to Nascimento et al. [63], these changes reflect decisions made in response to various economic and political contexts. Local, regional, and global factors significantly influence deforestation and land use changes in the Brazilian Amazon. These factors include the conversion of forests into pastures and pastures into agricultural areas, encouraged by the global demand for agricultural commodities such as soybeans and corn [64]. According to Vieira et al. [65] and Souza et al. [66], livestock farming is responsible for approximately 80% of illegal deforestation.

The observed results confirm the model of progressive degradation described by Vallim and Leichsenring [67]. This model posits that the Brazilian Amazon is undergoing a structured process involving selective logging, extensive livestock farming, and irregular land appropriation. Initially, tree species with the highest commercial value are removed, which has led to increased deforestation and pasture development, often associated with land grabbing. Including livestock production in formal marketing chains, particularly through the industrial processing of meat, ensures the financial sustainability of these activities, even in illegally occupied areas. This context helps explain why approximately 20% of the original forest cover has been converted into pastures over the last 40 years, as noted by [68–70].

To understand livestock farming and agricultural expansion in the Brazilian Amazon, one must consider the economic, social, and political factors that influence changes in land use and cover. The expansion of agricultural frontiers, particularly for the production of commodities such as soybeans, corn, and beef, has been strongly encouraged by economic incentives, including subsidies, rural credit, and investments in logistics infrastructure [71–74].

Since the 1970s, public policies have promoted occupying the Brazilian Amazon as a development and integration strategy. These incentives have resulted in the establishment of agricultural expansion zones in areas that were once covered by native forests. This has contributed to the consolidation of a development model that is based on the intensive exploitation of natural resources [75]. Growing land values and increased international demand for agribusiness products have increased pressure on the Amazonian territory, particularly in states such as Mato Grosso, Pará, and Rondônia [76].

Social and political factors also play a decisive role in this process. The lack of land regularization, illegal occupation of public lands, and concentration of land ownership on large properties encourage the uncontrolled growth of agricultural activities, frequently in protected areas or within the territories of indigenous peoples and traditional communities [77,78].

The weakening of Brazilian environmental agencies, the reduction in resources allocated to enforcement, and political discourse that minimizes the importance of environmental conservation have all contributed to the advance of the agricultural frontier into primary forest areas [79].

Furthermore, recent changes in environmental legislation and proposals to weaken environmental licensing requirements have created a permissive regulatory environment that favors the expansion of agricultural and infrastructure enterprises, even in ecologically sensitive areas [80]. Together, these factors contribute to intensified environmental degradation and land use transformation, which threatens the ecological integrity of the Amazon biome. More effective and integrated public policies are required to mitigate these impacts and ensure regional sustainability.

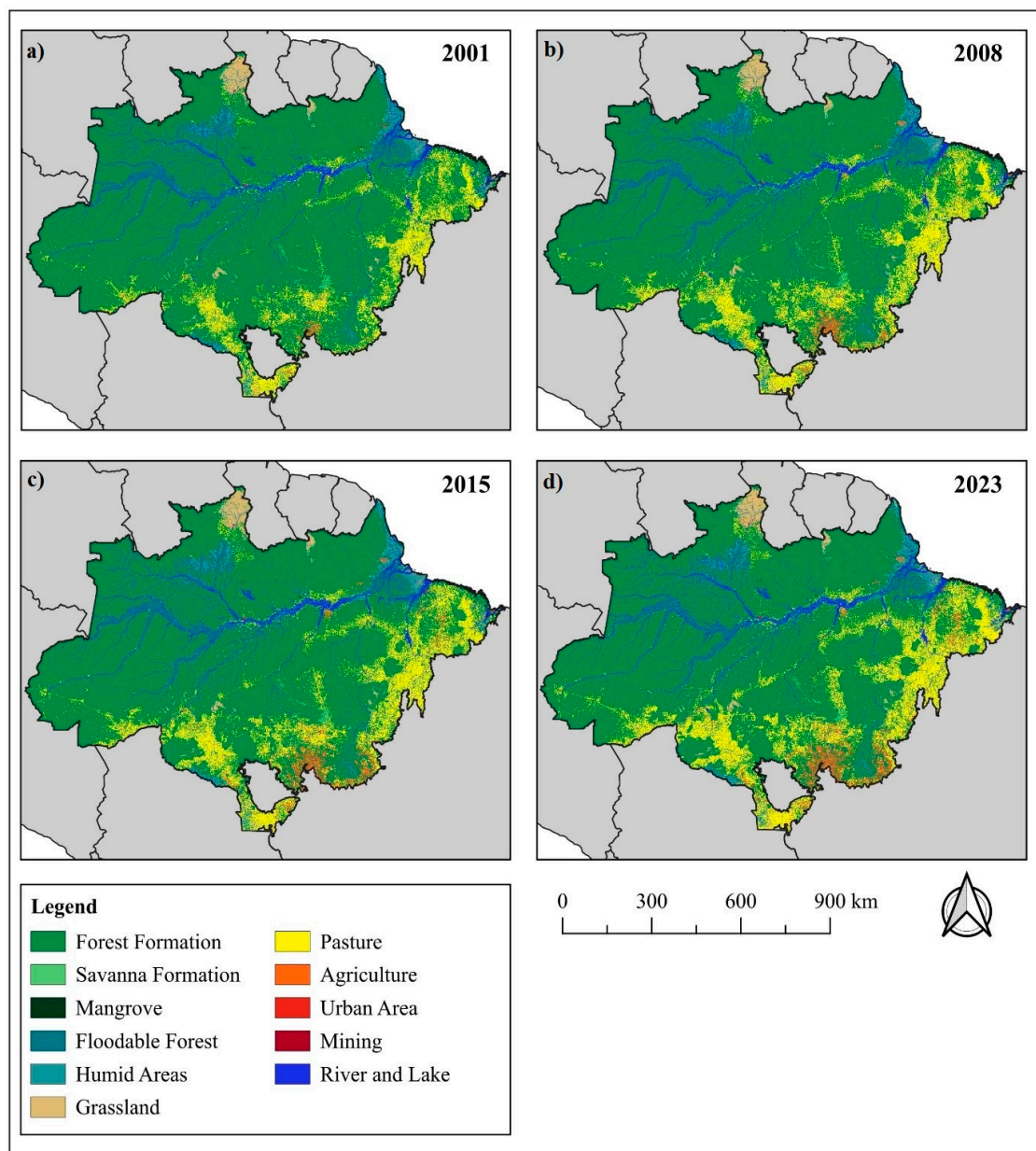
In addition to the expansion of pasture and agricultural areas, a significant increase in mining activity occurred during the evaluation period. These findings align with those of Azevedo-Santos [81] and Montalván et al. [82], who identified mining as a primary cause of environmental degradation in the Brazilian Amazon and surrounding regions. This degradation includes the construction of access roads, the establishment of camps, and the creation of waste disposal areas. These factors contribute significantly to the loss of forest cover, even within conservation areas and Indigenous Territories.

Mining directly affects the landscape's structure by fragmenting forest remnants and altering local ecosystems' functioning. Asner et al. [83] discovered that expanding mined areas alters the hydrological regimes around extraction sites. This affects water bodies and wetlands, impacting biodiversity and water resource dynamics. In addition to these direct impacts, the construction of access roads for mining can facilitate the expansion of land uses, such as livestock farming and agriculture, further exacerbating environmental degradation.

The results of this study support these observations, demonstrating that mining has become a critical factor in landscape transformation. The overlap between mining areas and agricultural frontier zones highlights the need for more effective monitoring and public policies that address the cumulative impact of various human-caused pressures on remaining forest formations.

The spatial distribution of LULCC in the Brazilian Amazon from 2001 to 2023 reveals that forest loss was most pronounced in the southern and eastern regions, coinciding with the edges of the biome, where livestock and agricultural expansion expand (Figure 3). This region is known as the "arc of deforestation", an area that extends from the eastern and southern state of Pará to the states of Mato Grosso, Rondônia, and Acre [84]. It

is characterized by increased agricultural activity and expanding infrastructure, which leads to the fragmentation of native vegetation due to territorial occupation and local economic dynamics.



**Figure 3.** Spatial distribution of Land Use and Land Cover Classes (LULCC) in the Brazilian Amazon in the years of (a) 2001, (b) 2008, (c) 2015, and (d) 2023.

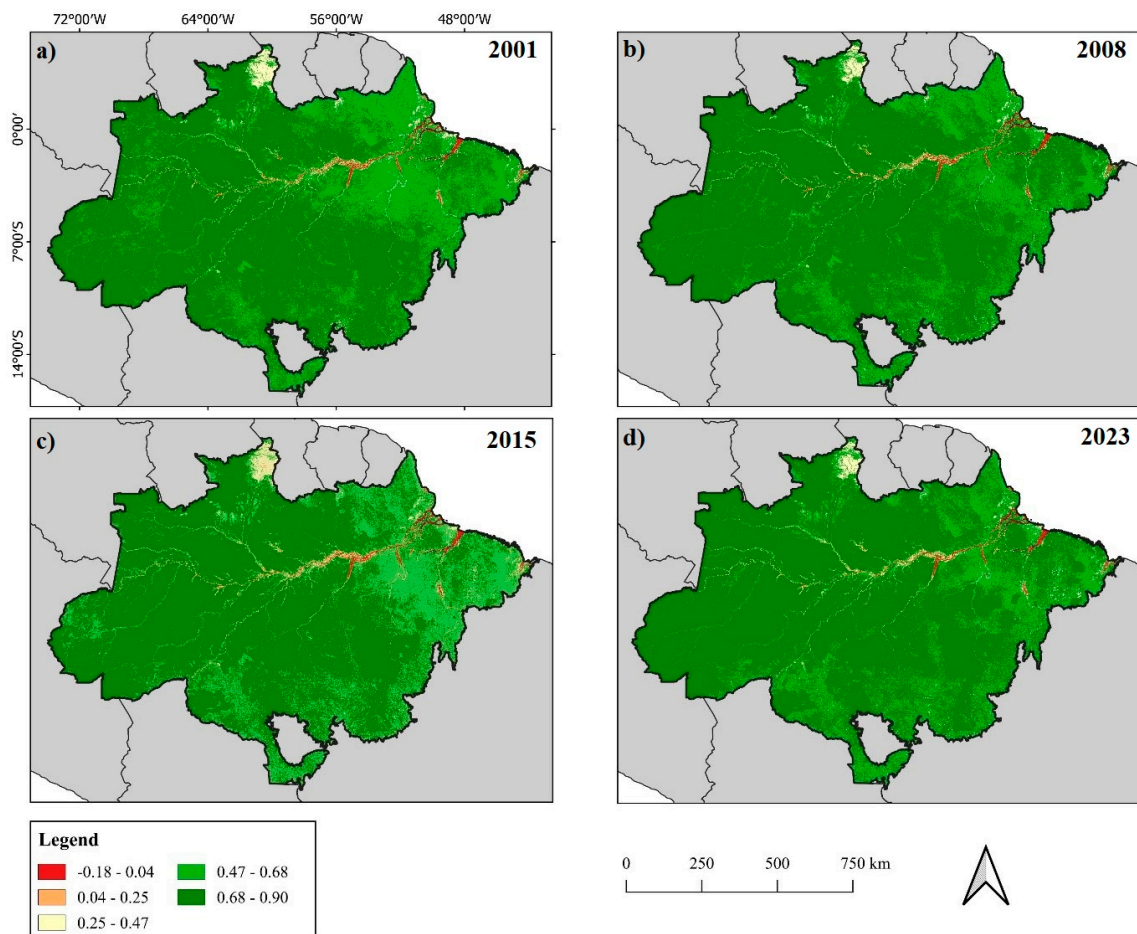
In addition to the aforementioned information on the Brazilian Amazon from 2001 to 2023, we present the annual variation in deforested areas and the total area burned by fires. We also illustrate the spatial distribution of accumulated deforestation and burned areas (see Supplementary Materials, Figures S1–S3).

The replacement of forests with pastures and agricultural crops does not occur uniformly. Rather, it varies according to the socioeconomic context of each region. For example, large-scale production has accelerated deforestation in Mato Grosso state. In contrast, forest loss in the states of Rondônia and Acre reflects more diffuse or specific patterns, though it is also increasing [85]. The peripheral location of these transformations accentuates the “edge effect”, resulting in ecological impacts such as the loss of biodiversity, micro-

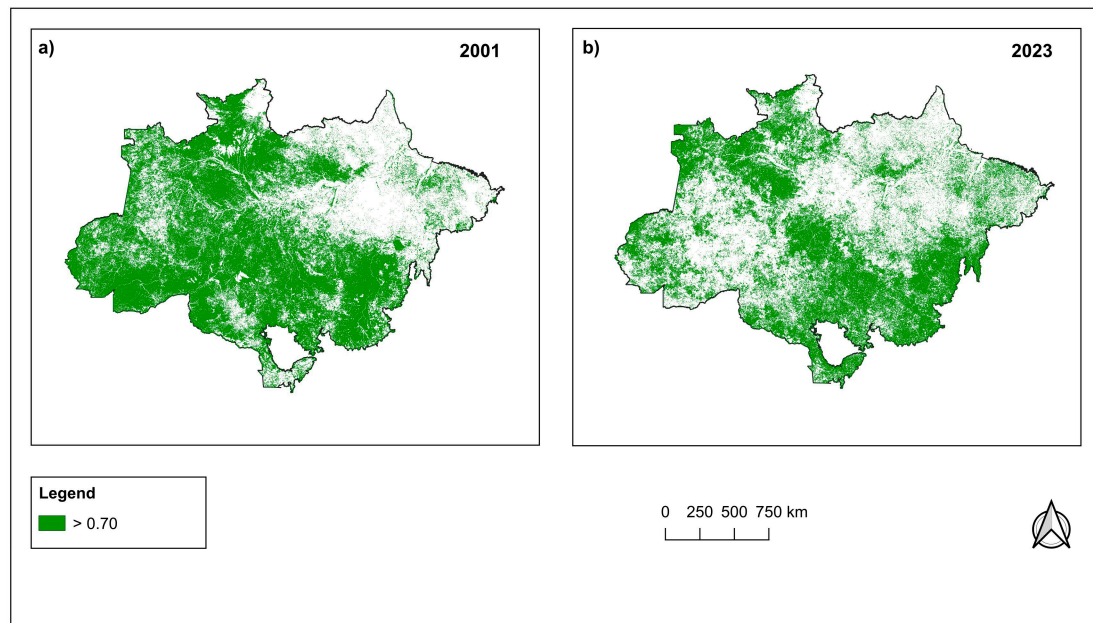
climatic changes, and reduced biome resilience. These findings underscore the need for public policies that curb deforestation and protect remaining areas, especially in vulnerable transition zones.

During the analyzed period, the NDVI values in the Brazilian Amazon fluctuated, indicating changes in vegetation coverage and land use (Figure 4). Areas containing water bodies exhibited negative values ranging from  $-0.18$  to  $0.04$  and appeared as red on the maps. Meanwhile, areas with sparse vegetation or exposed soil had values between  $0.04$  and  $0.47$ . Regions with dense vegetation, primarily in the northern part of the region, had values above  $0.47$ , reaching  $0.90$  in areas with greater plant biomass. Spatial analysis reveals a reduction in vegetation density in certain regions, particularly along major highways and in areas with higher rates of conversion for agricultural activities (Figure 5). Deforestation, especially along the edges of the biome, has increased areas with lower NDVI values over the decades, indicating progressive vegetation cover degradation in previously forested areas.

Areas with high NDVI values (above  $0.47$ ), which are associated with dense forests, remained relatively stable in the central regions of the biome. However, the southern and eastern edges exhibited a significant decline, consistent with previous studies on deforestation [86]. The loss of vegetation along highways such as the BR-163 and the BR-230 (also known as the Trans-Amazonian) coincides with areas of intense land use change, indicating ongoing fragmentation of forest remnants driven by agricultural expansion [87].



**Figure 4.** Spatial distribution of NDVI values in the Brazilian Amazon between the years of (a) 2001, (b) 2008, (c) 2015, and (d) 2023.



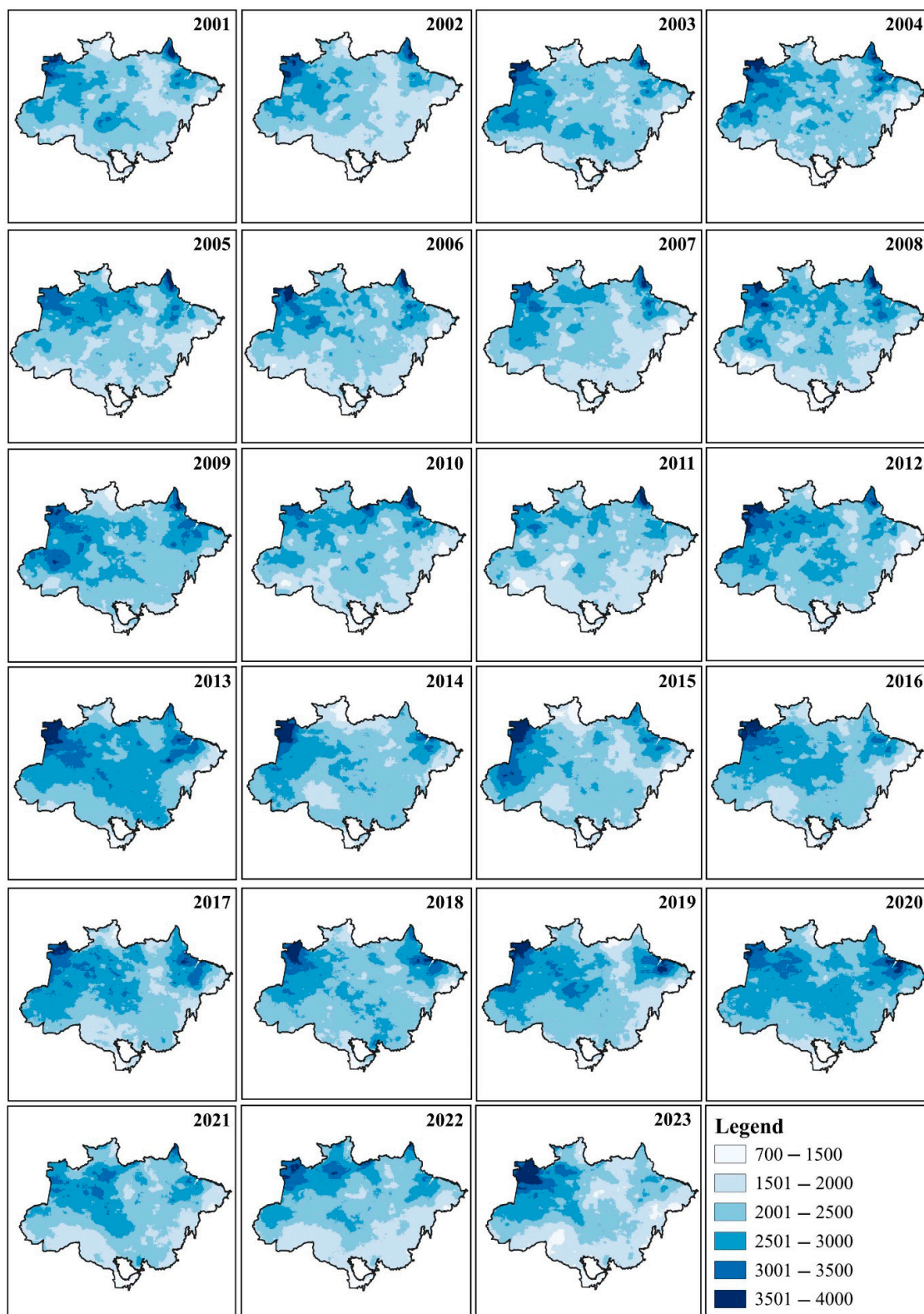
**Figure 5.** Normalized Difference Vegetation Index (NDVI) values of areas with dense vegetation in the Brazilian Amazon in 2001 (a) and 2023 (b).

An increase in medium and low NDVI values (between  $-0.18$  and  $0.47$ ) indicates sparse vegetation, exposed soil, and human-used areas. This pattern highlights the degradation of native vegetation and its replacement by non-forest uses [88]. These changes significantly impact the ecological balance, resulting in altered hydrological cycles, increased surface temperatures, and a reduced carbon sequestration capacity [89,90]. The concentration of these changes at the edges of the biome underscores the importance of initiatives targeting these transition zones. These zones are more susceptible to human impact and are vital for the ecological connectivity and resilience of the Brazilian Amazon [91].

Figure 6 shows the spatial distribution of average annual precipitation in the Brazilian Amazon from 2001 to 2023. The years of 2009, 2012, and 2017 experienced the highest precipitation, with large areas receiving over 2500 mm. Conversely, 2010, 2016, and 2020 had lower amounts of precipitation, indicating reduced average precipitation across much of the region.

The reduction in precipitation observed in various regions of the Brazilian Amazon between 2001 and 2023 is likely associated with changes in LULCC. Replacing the forest cover with pastures and crops has profoundly altered the surface hydrological balance in these areas. This pattern aligns with previous studies showing that large-scale deforestation alters the formation of precipitation by reducing evapotranspiration, which plays a key role in the recycling of atmospheric moisture in the Amazon basin [92]. Reduced vegetation cover directly affects the flow of water vapor into the atmosphere, compromising cloud formation and, consequently, regional precipitation [93,94].

Furthermore, the loss of vegetation contributes to changes in energy flows, including increased sensible heat and reduced latent heat. Vegetation loss also causes physical changes to the surface, including increased albedo and decreased roughness. These changes reduce the efficiency of local convection, the main mechanism for generating precipitation in the dry season [95]. Since up to 70% of precipitation in the southern Amazon basin comes from recycled forest moisture [96,97], deforestation compromises the region's climate resilience. Thus, the reduction in precipitation during the analyzed period is due to both interannual climate variability and a structural trend of degradation of regional atmospheric processes induced by human actions.



**Figure 6.** Spatial distribution of average annual precipitation in the Brazilian Amazon from 2001 to 2023.

The El Niño phenomenon significantly impacts precipitation patterns in the Amazon, especially during intense events such as those in 2010 and 2015/2016. These events are linked to the anomalous warming of equatorial Pacific waters, which disrupts tropical atmospheric circulation and hinders the formation of convective clouds over the Amazon

basin [98]. Consequently, dry periods intensify, severely impacting the central and eastern regions of the Brazilian Amazon.

The combined effects of El Niño and deforestation exacerbate droughts, creating negative feedback loops that increase susceptibility to fire and further vegetation loss. Frequent extreme weather events and changes in land use disrupt the forest's hydrological regime, which threatens the stability of the regional climate system [99,100].

Figure 7 shows how LST varied in the Brazilian Amazon from 2001 to 2023. Note that there was an increase in areas with temperatures between 30 and 34 °C in the years of 2015, 2016, 2020, and 2023, indicating a warming trend. The 26–30 °C class exhibited variability over time, with reductions in certain periods and increases in others, notably surging after 2017. Furthermore, the distribution of areas with temperatures between 26 and 30 °C was greater in 2009, 2012, and 2021, while the presence of the 22 and 26 °C range was greater in 2001, 2005, and 2010.

The increase in LST reflects a complex interaction between natural and anthropogenic factors. The increase in areas experiencing temperatures between 30 and 34 °C in 2015, 2016, 2020, and 2023 suggests an intensification of the regional warming process. This process is often associated with extreme events such as severe droughts and heat waves [101]. These years coincide with large-scale climate events, such as El Niño, which reduces precipitation and increases insolation in the region, favoring surface warming [102].

In addition to natural climate variability, deforestation, the intensification of agricultural activities, and the expansion of pastureland play a crucial role in the increase in LST. Replacing forest cover with exposed surfaces or lower-density vegetation reduces ET and alters the energy balance, promoting an increase in surface temperature [103]. Removing native vegetation reduces albedo and the soil's water storage capacity, accentuating local warming, especially during dry periods [104].

The results of this study align with the surface warming patterns observed in previous investigations of the Brazilian Amazon. For instance, Jiménez-Muñoz et al. [105] identified surface temperature anomalies during the dry season of 2005. These anomalies were concentrated in the southwestern and northeastern regions of the forest. In 2010, the anomalies were more intense and widespread, particularly in the southeastern part of the biome. The vegetation's response to these drought events confirmed the spatial distribution of the anomalies [106]. The present analysis also identified these patterns, with areas predominantly within the 22–26 °C range in 2005 and 2010. The data suggest an increasing trend of surface warming, exacerbated by climate extremes like those caused by the El Niño event and by advancing deforestation in the region, particularly after 2015.

Figure 8 shows how ET has varied in the Brazilian Amazon during the studied period. During the initial years (2001–2005), areas with medium-to-high ET values (1361–2200 mm) predominated, with wide distributions of light and medium green. From 2010 onward, there was a gradual reduction in areas with higher ET (2201–2650 mm, dark green), indicating a potential shift in water availability patterns and climate conditions. Between 2015 and 2020, areas with reduced ET (100–940 mm, red and orange) expanded in some regions, particularly during intense droughts. However, there was partial recovery in the subsequent years (2021–2023), as evidenced by an increase in areas of moderate ET (1361–1780 mm, light green) and the stabilization of the 1781–2200 mm class (medium green).

The reduction observed in areas with high ET values between 2001 and 2023 in the Brazilian Amazon is related to changes in LULCC, as well as an increased frequency and intensity of drought events. These findings align with the evidence of Paca et al. [107] of a strong correlation between forest cover density and ET intensity. Together, these studies reinforce the idea that converting forested areas for other uses significantly reduces ET in the Brazilian Amazon.

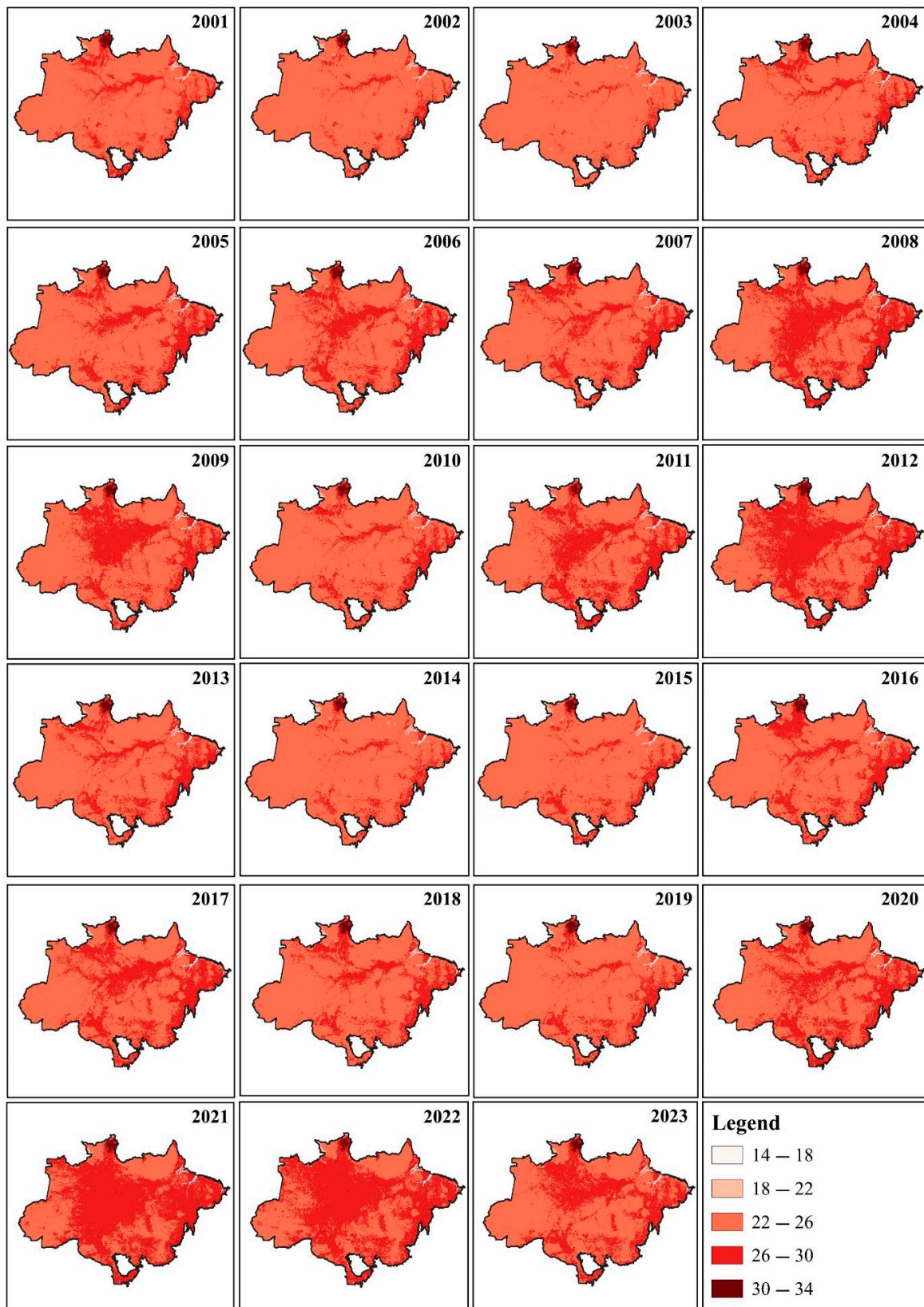
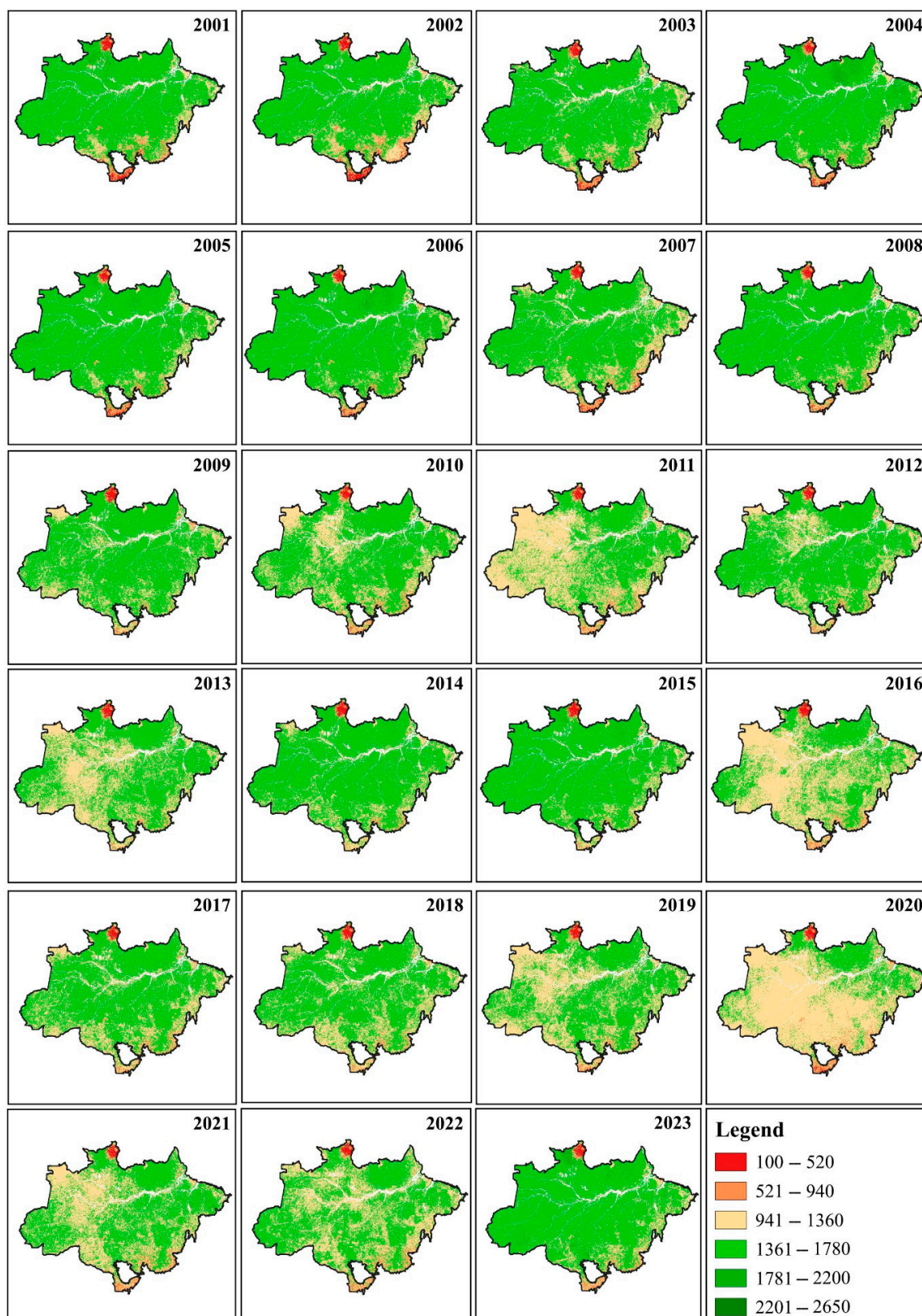


Figure 7. Spatial distribution of land surface temperature (LST) in the Brazilian Amazon from 2001 to 2023.



**Figure 8.** Spatial distribution of mean annual evapotranspiration (ET) in the Brazilian Amazon from 2001 to 2023.

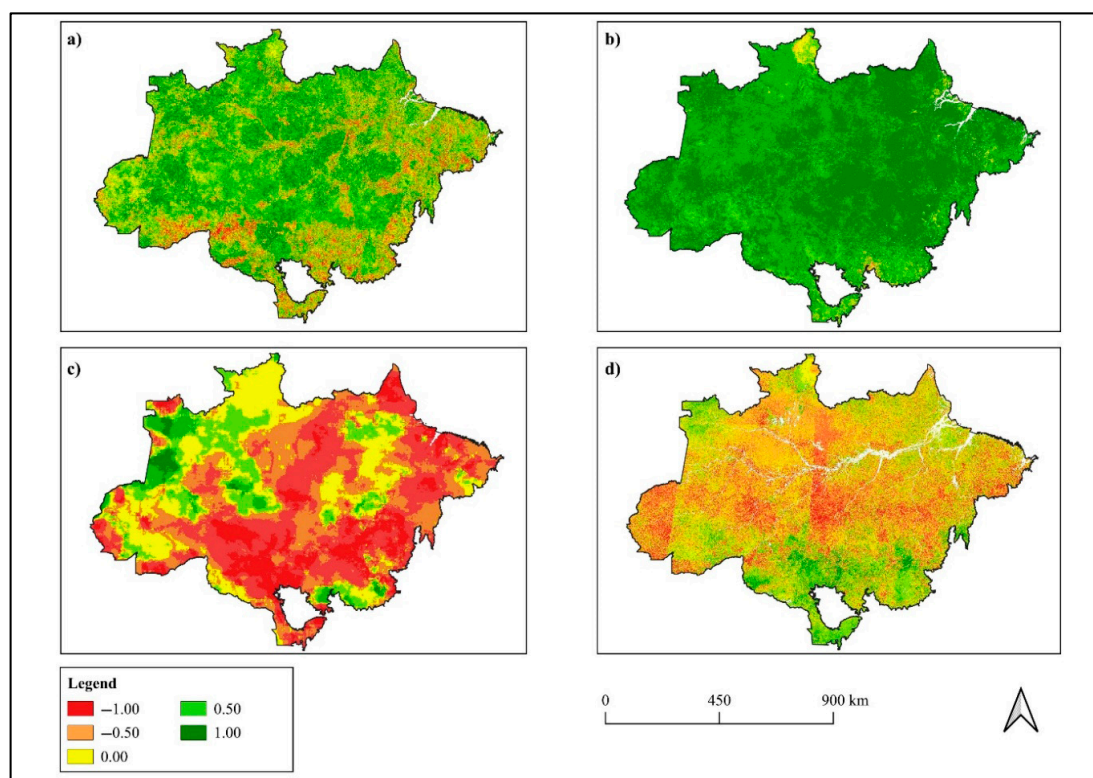
Furthermore, the Brazilian Amazon has adapted to maintain stable ET rates during the dry season through deep root systems that access water stored in deep soil layers [108]. However, prolonged water stress conditions associated with severe droughts can compro-

mise this resilience. Extreme drought events, such as those in 2005, 2010, and 2015, reduce ET not only in the year they occur, but also in subsequent years, due to structural damage to the forest canopy that affects the transpiration capacity of the vegetation [109–111]. This helps explain the expansion of areas with reduced ET observed between 2015 and 2020. The partial recovery of ET between 2021 and 2023 may reflect reduced climate anomalies and possible plant regeneration processes. However, this recovery is insufficient to reverse the general trend of ET decline in the biome. Thus, these results reinforce the growing vulnerability of the Brazilian Amazon to climate and anthropogenic changes.

The southern and southeastern regions of the Brazilian Amazon generally have a drier climate with a prolonged dry season that directly influences vegetation dynamics. Significant reductions in ET during dry periods are common in these regions and impact the ecophysiological processes of plants, resulting in leaf loss and dormancy [112]. This vegetation response is associated with a climate pattern similar to that of savannas, where water limitation strongly regulates ecosystem functioning.

In addition to their natural climate characteristics, these regions coincide with the “arc of deforestation” an area experiencing some of the highest rates of land cover change in the Brazilian Amazon. The conversion of forests for agricultural use has intensified environmental degradation, altering the surface and reducing its capacity to retain moisture, which affects regional ET.

The results of the Mann–Kendall test revealed significant environmental changes in the Brazilian Amazon between 2001 and 2023 (Figure 9). The NDVI showed a declining trend primarily along the edges of the biome, particularly in the southern and eastern regions. Meanwhile, central and northern areas exhibited less significant variations (Figure 9a). Agriculture and logging have led to forest loss, replacing native vegetation with pastures and crops [113]. This conversion reduces biomass, vegetation cover, and ecosystem integrity, which is evidenced by declining NDVI values.



**Figure 9.** Mann–Kendall test analysis in the Brazilian Amazon, (a) NDVI, (b) land surface temperature, (c) precipitation, and (d) evapotranspiration.

The increase in LST in the southern, eastern, and central biome areas (Figure 9b) confirms previous findings that deforestation and degradation increase albedo and reduce ET, resulting in surface warming [114]. Additionally, the observed warming may be related to an increased frequency of extreme events, such as droughts and heat waves, which are amplified by the El Niño phenomenon and changes in the region's climate regime [115].

Precipitation decreased significantly in the central, southern, and western regions (Figure 9c), which could directly impact the region's hydrological regime, the availability of water for vegetation, and primary productivity [116]. This trend is especially alarming in a biome whose ecological structure depends on consistent precipitation and the recycling of water vapor facilitated by the forest.

ET exhibited mixed patterns, with a reduction primarily in the south and southeast (Figure 9d), where forest conversion for agriculture is prevalent. The decrease in ET in areas converted to agriculture was expected since secondary vegetation and agricultural crops have lower transpiration capacities than primary forests [117,118]. Conversely, an increasing trend was observed in the west and some central regions. The increase in preserved areas may reflect the physiological response of vegetation to thermal and water changes, or the greater availability of energy for evaporation in heated areas with dense vegetation.

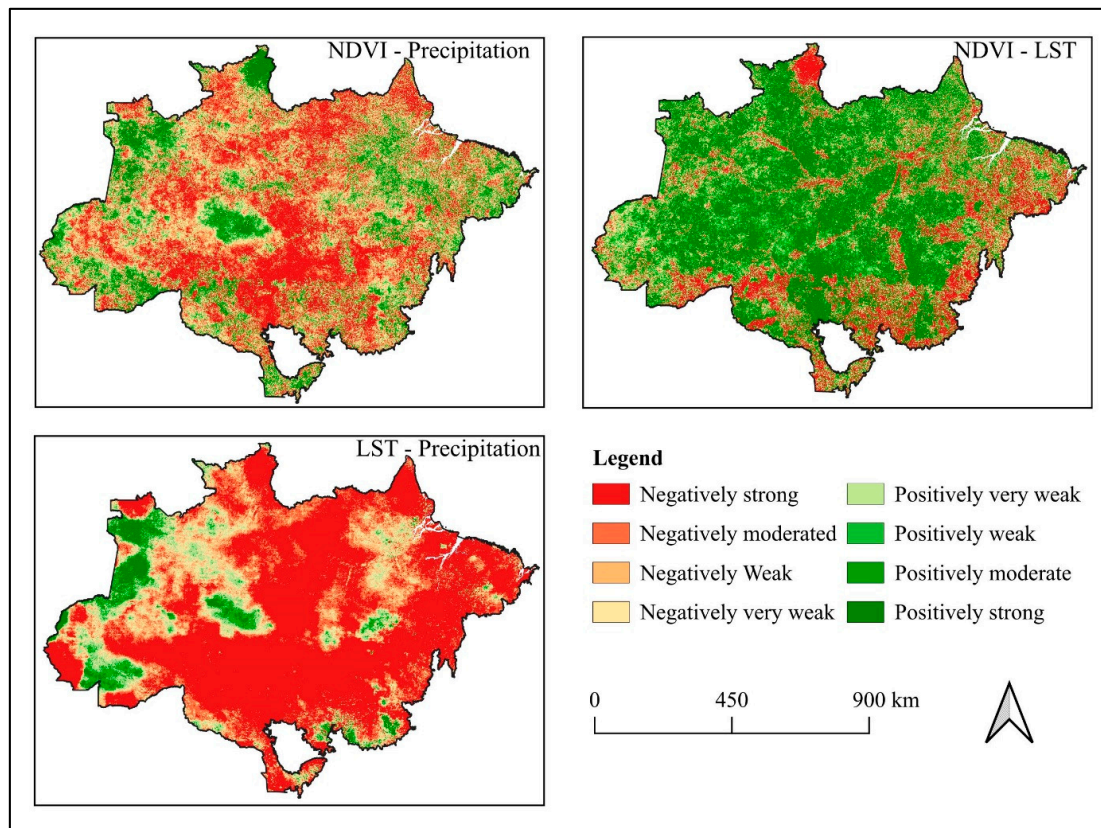
The results for the Brazilian Amazon reveal concerning environmental trends that reflect processes within the biome and patterns observed throughout Brazil. The decline in NDVI values along the southern and eastern borders of the region is consistent with the expansion of the agricultural frontier. A similar pattern has been observed in the Cerrado, where the intensification of agriculture and livestock farming has caused the accelerated loss of native vegetation and increased ecological fragmentation [119]. Similarly, studies in the Pantanal biome have identified significant reductions in vegetation indices due to the expansion of pastures and changes in the hydrological regime, especially since 2000 [120]. These findings confirm that the decline of vegetation transcends the boundaries of the Brazilian Amazon.

The increase in LST and the decrease in ET observed in much of the Brazilian Amazon have also been reported in other studies. Baker and Spracklen [121] found that deforestation contributed to decreased ET and increased temperatures in the region between 2000 and 2013. They determined that a 39.8% reduction in tree cover resulted in an average LST increase of 0.44 °C, with variations reaching 1.5 °C between preserved forests and heavily degraded regions during the dry season. Similarly, Li et al. [122] demonstrated, based on satellite observations, that the conversion of forest areas to non-forest uses, such as agriculture and pasture, can cause a significant increase in surface temperature, especially in tropical regions, with average increases exceeding 0.5 °C. This conversion also led to a reduction in ET. Taking a more comprehensive approach, Prevedello et al. [123] reported an average LST increase of 1.08 °C in areas that lost approximately 50% of their forest cover over the same time period.

The downward trend in precipitation in the south-central and western Brazilian Amazon is particularly concerning, as this region plays a crucial role in recycling water vapor and maintaining the precipitation pattern across much of South America [124]. Studies indicate a reduction in annual precipitation and changes in seasonality in the Pantanal, impacting flood dynamics and biodiversity directly [125,126].

The correlation maps revealed distinct patterns within the observed variations (Figure 10). The NDVI–precipitation map showed a moderate to strong negative correlation across much of the central and southern regions. This suggests that decreased precipitation is linked to reduced vegetation, confirming previous studies that highlighted the direct

relationship between the two [127]. However, the positive correlations in the far north and west could indicate regions with greater vegetation resilience or lower human impact.



**Figure 10.** Correlation map between variables, NDVI, LST, and precipitation in the Brazilian Amazon.

The NDVI–LST map revealed mostly weak to moderate positive correlations, suggesting that a higher LST tends to reduce NDVI, possibly due to vegetation adaptation or heat-tolerant species. However, moderate to strong negative correlations were observed at the edges and in some southern and northern areas, indicating that increased temperature is associated with reduced vegetation in these regions [128]. Dos Santos et al. [129] found a negative correlation between LST and NDVI in the Brazilian Amazon, indicating that rising temperatures may impair vegetation functionality on a large scale.

The LST–precipitation map revealed a strong negative correlation in the center, south, and east of the region, indicating that reduced atmospheric humidity favors surface warming and intensifies the effects of regional climate change [130]. In contrast, areas in the west exhibited a weak-to-moderate positive correlation. These patterns highlight the importance of an integrated analysis to understand the combined effects of climate and vegetation cover.

The results demonstrate the effectiveness of Mann–Kendall and correlation statistical methods in analyzing environmental time series that are not strongly influenced by seasons. These methods enable the identification of significant trends and consistent patterns of change. They highlight the direct relationship between the loss of vegetation cover and changes in climate regimes, especially in ecologically sensitive regions like the Brazilian Amazon.

The analysis reinforces the idea that large-scale deforestation compromises the ecological integrity of biomes and affects atmospheric processes. These alterations result in changes to the spatial and temporal distribution of precipitation and intensify thermal variations. These impacts can trigger negative feedback cycles on the remaining vegetation,

further aggravating environmental degradation. Therefore, it is crucial to understand the relationship between changes in land use and climate variables to grasp the effects of human actions on tropical ecosystems. This underscores the urgent need for integrated conservation and mitigation strategies.

As with all analyses, it is important to note that the estimates of LULCC derived from satellite imagery have limitations that must be considered when interpreting the results. The main sources of uncertainty are the sensors' spatial resolution, which may fail to capture small patches of vegetation or bodies of water, and the presence of clouds, shadows, and seasonal variations that interfere with image quality.

Temporal consistency may also be compromised by differences between sensors, changes in classification algorithms, and the lack of validation with field data, all of which limit the reliability of the analyses. Therefore, recognizing these methodological limitations is crucial to avoid misinterpretations and ensure greater rigor when analyzing environmental changes over time.

#### 4. Conclusions

This study demonstrated that changes in land use and occupation in the Brazilian Amazon between 2001 and 2023 resulted in reduced native vegetation cover and increased pasture and agricultural areas. These changes directly impacted the assessed environmental parameters, compromising the region's climatic and ecological stability. The changes increased surface temperatures and reduced precipitation and evapotranspiration.

In addition to emphasizing the importance of curbing deforestation, the results of this study provide practical technical support for public policy. Spatial trend maps of the Normalized Difference Vegetation Index, land surface temperature, precipitation, and evapotranspiration indicators help identify areas experiencing vegetation loss and intensified heat stress. This information is crucial for defining priority regions for conservation, restoration, and environmental monitoring.

Data from this study can guide the review of ecological-economic zoning, support territorial planning, and inform local, state, and federal decisions. Integrating scientific evidence into environmental management strengthens the work of oversight agencies and public policies focused on sustainability, ensuring more effective, targeted actions to protect the Amazon rainforest.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su17157099/s1>: Figure S1: (a) Annual variation in deforested areas in the Brazilian Amazon from 2001 to 2023; (b) Total area burned by fires in the Brazilian Amazon from 2001 to 2023; Figure S2: Spatial distribution of accumulated deforestation in the Brazilian Amazon from 2001 to 2023; Figure S3: Spatial distribution of accumulated burned areas in the Brazilian Amazon from 2001 to 2023.

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