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Abstract

The study examines the relationship between water surface loss and deforestation in the Brazilian Amazon, focusing on the expansion of farming (crops and agriculture, as well as pasture and livestock) and the impact of inadequate legislation from 1985 to 2023. The Amazon biome is vital for the global hydrological cycle and is home to about 10% of the known species. Data from MapBiomas and multivariate statistical techniques revealed that forest and water surface areas decreased significantly while pasture and agricultural regions increased. Environmental legislation has shown progress, with Center and Left-leaning governments implementing environmental protection measures. In contrast, Center-Right and Right-leaning governments prioritized economic interests, resulting in significant setbacks in forest protection and increased deforestation. The study further highlights the importance of developing integrated and sustainable strategies that balance economic development and environmental conservation in the Amazon biome.

Keywords: multivariate analysis; PCA-Factorial; cluster; pasture; agricultural; governments

1. Introduction

Historically, Brazil is a country that has long-standing environmental concerns, with one of the first actions to protect forests and river basins dating back to the imperial period, when the capital at the time, Rio de Janeiro, began to suffer from a lack of water during the first half of the 19th century in the heart of the Atlantic Forest [1]. At the beginning of the 20th century, water was already considered a public good in the Civil Code of 1916 [2].

The occupation of different regions of Brazil occurred at distinct moments throughout the country's history. The situation in northern Brazil began to change in the late 1950s, with the creation of the Manaus Free Trade Zone (Decree No. 3,173/1957). Throughout the 1960s, the military government initiated the construction of the Trans-Amazonian Highway (BR-230). It also supported policies aimed at allocating land to farmers and ranchers [3], allowing them to occupy the large "empty" spaces in the Amazon region, to declare sovereignty over the area [4]. This policy was intensified in the 1970s, under the pretext of economically integrating the region with the rest of Brazil [5], through a colonization process that was slower than the rest of the country, but which resulted in accelerated deforestation [6,7].

The Amazon rainforest is the most emblematic biome in South America, of which approximately 60% is located in Brazilian territory and is present in seven other countries (Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela), in addition to the French Guyana region [8,9]. The Amazon plays a fundamental role in the hydrological cycle and, consequently, in the global climate [10–12], as the forest significantly contributes to cloud formation and precipitation through transpiration and evapotranspiration [13]. This cycle is crucial for South America's local and adjacent ecosystems, water supply, and agriculture, particularly in central and southeastern Brazil. Besides that, regional water bodies such as the Amazon River host numerous endemic species of fish, aquatic mammals, birds, and plants [14], recalling the intrinsic value of its biodiversity [15].

The relationships among these ecological components, however, are deeply affected by land-use change processes. Recent research in the Amazon has highlighted the intricate and dynamic relationships between forest loss, changes in surface water extent, and agricultural expansion. Deforestation often leads to significant reductions in water surface area, as the removal of forest cover disrupts the hydrological cycle, reduces local precipitation, and accelerates runoff and sedimentation in rivers and lakes [16,17]. Agricultural and pasture[1] expansion, as primary drivers of deforestation, intensify these effects by replacing native vegetation with land uses that impairs evapotranspiration rates and lower capacity for water retention [18,19]. These land-use changes not only affect biodiversity and carbon sequestration but also directly impact water availability, regional climate regulation, and the resilience of both terrestrial and aquatic ecosystems. Understanding these coupled processes is essential for designing effective conservation strategies and land-use policies in the Amazon, as they reveal feedback mechanisms that can exacerbate ecosystem degradation and compromise long-term sustainability.

The loss of forest cover due to the expansion of agricultural and pasture areas, coupled with climate change, increasingly contributes to forecasts of more intense and prolonged drought periods [16,20–22], affecting also the carbon cycle [17] and the ability of its resultant sequestration of the forest. These factors can compromise the forest's capacity to adapt [18], and especially, to regenerate (return to its original state), which is linked to the concept of environmental resilience, facilitating the reaching of the "point of no return" [12,23].

The critical threshold itself is still the subject of debate, but we all know that it is intensified by human action (i.e., land use and global climate change). Forcing the region to undergo a climate transition due to degradation caused by the misuse of land and water [24] and potentially transforming the Amazon into a "savanna-like" ecosystem [25], with a decrease in the original forested area and average precipitation, which would harm biodiversity and essential ecosystem services, including water production and conservation, as well as the environmental and economic sustainability of the Amazon [19,26,27]. This would result in a regional [28] and possibly global [3] climate catastrophe, the consequences of which are not yet fully understood.

The region has experienced a history of "ups and downs" regarding its protection due to dubious public policies. The Brazilian environmental legislation's starting point was the 1934 Forest Code (Decree No. 23,793, under the first Getúlio Vargas administration), which established guidelines for the use and conservation of forests. In the 1960s, the creation of the Brazilian Institute of Forest Development (*Instituto Brasileiro de Desenvolvimento Florestal* – IBDF) and the updated 1965 Forest Code (Law No. 4,771) intensified regulatory efforts [29,30].

Starting in the 1980s, the National Environmental Policy (Law No. 6,938/1981) and the creation of the National Environmental System (*Sistema Nacional do Meio Ambiente* – SISNAMA) and the National Environmental Council (*Conselho Nacional do Meio Ambiente* – CONAMA) consolidated the administrative structure for environmental management. And after the end of the military government (which lasted 21 years), the 1988 Brazilian Constitution brought significant advances by recognizing the Amazon as a national heritage and imposing limits on its exploitation. By the late 1980s, the Brazilian government was being held responsible for large-scale deforestation in the Amazon due to colonization policies. In response to this crisis, the Annual Monitoring of Native Vegetation Suppression (PRODES) was established by the National Institute for Space Research

[1]Agricultural and pasture subclasses terminology used by MapBiomas to describe livestock and farming areas.

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(INPE) to quantify annually the loss of natural vegetation in the Amazon. This initiative contributed to the government's efforts to address the situation [31].

In the 1990s, international pressure and internal awareness led to the implementation of new policies, such as the Action Plan for the Protection of Brazilian Tropical Forests and the creation of the Brazilian Institute of Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA), which centralized the enforcement and implementation of environmental policies [29,30,32–34]. In response to public opinion and to control deforestation, then-President Fernando Henrique Cardoso established, in the following year, Provisional Measure No. 1,511 of July 15, 1996, which increased the Legal Reserve (LR) requirement on properties located in the Amazon from 50% to 80% [35].

Following the Earth Summit in 1992, the country assumed a prominent role in the global climate debate. From the end of the 1990s to the 2000s, after making some progress with national environmental legislation, Brazil intensified its efforts to control deforestation in the Amazon, launching the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (*Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal* – PPCDAm) in 2004. The Daily Monitoring of Suppression and Degradation of Native Vegetation (DETER), established under the PPCDAm and implemented by INPE in 2004, began issuing daily alerts of deforestation and forest degradation. This enabled the identification of priority areas for enforcement and the increased application of environmental fines [36]. This plan significantly reduced deforestation rates. However, the revision of the Forest Code in 2012, which relaxed protection rules, was seen as a major setback [37] from the previous century.

Brazilian environmental policy has faced increasing deforestation rates and frequent legislative changes that favor agricultural expansion and the exploitation of natural resources. This trajectory shows gradual development from initial sparse measures to a more consolidated structure in the 1980s and 1990s, with the most recent obstacles arising during the Bolsonaro administration (2019–2022), a period characterized by severe budget cuts to environmental agencies, weakened enforcement of environmental laws, an unprecedented increase in the approval of pesticides, repeated attempts to relax environmental licensing, and political interference in scientific and monitoring institutions [27,38–40].

Thus, this study seeks to analyze the statistical associations—and, in several cases, plausible causal relationships—between water surface loss, forest suppression (deforestation), and agricultural expansion (including crops and pasture) in the Amazon biome. These connections are explored in light of the temporal correspondence between land-use change events and major legislative shifts, as revealed by multivariate analysis. The research underscores the importance of initiatives such as MapBiomas, ongoing investment in remote sensing monitoring, and scientific research for producing robust empirical evidence. It also examines how successive changes in environmental legislation over the years have compromised the production and maintenance of water, an essential ecosystem service for the sustainability of the country and the planet [13,17,19,41].

2. Methodological Approach

2.1. Study Area

The Amazon biome, spanning nine South American countries (Brazil, Peru, Colombia, Venezuela, Ecuador, Bolivia, Guyana, Suriname) and territories (including French Guiana), is the world's largest contiguous tropical rainforest, with approximately 4.2 million km² of its total 5 million km² located in Brazil (Figure 1). This extensive region encompasses a wide array of climatic, topographic, hydrological, and ecological gradients, making it a critical hotspot for biodiversity and ecosystem services. Beyond its vast forest formations, roughly 7% of the biome is composed of non-forest vegetation types such as natural savannas, flooded grasslands, and campinas, all of which play significant roles in biodiversity maintenance and host numerous endemic species [42].

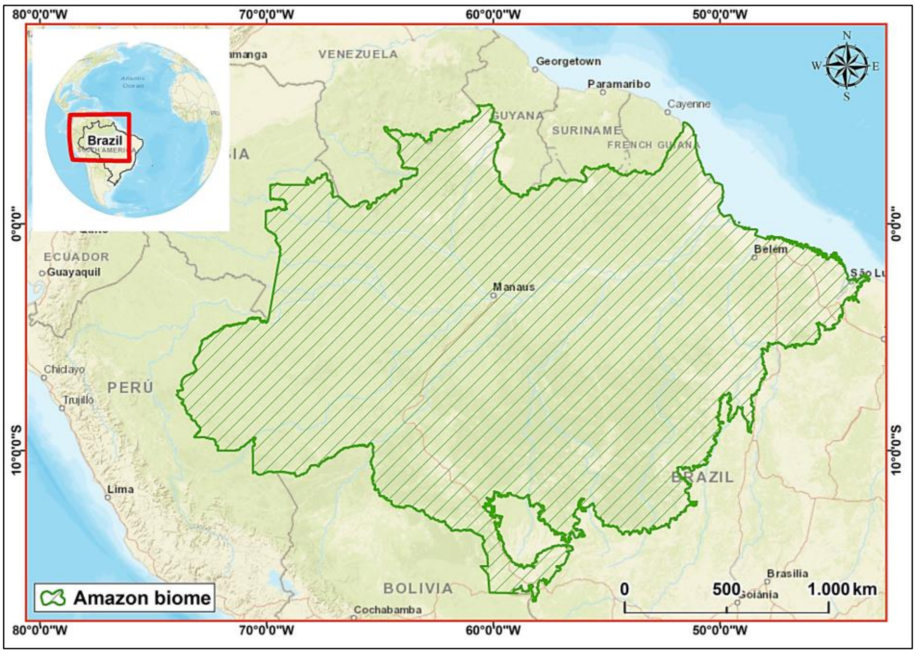

Figure 1. Amazon biome, Brazil.

The study area considered in this research corresponds to the legal boundaries of the Amazon biome in Brazil, as defined by the Brazilian Ministry of the Environment and adopted by the MapBiomas Project. This area was delineated using official cartographic bases and geospatial datasets, allowing precise extraction of land cover and hydrological variables at the biome scale. The Amazon is characterized by a humid equatorial climate, with mean annual temperatures ranging from 24 °C to 27 °C and annual rainfall between 1,700 and 3,600 mm [43]. Its hydrological network is dominated by the Amazon River and its tributaries, forming one of the world's most extensive and dynamic freshwater systems [44]. Despite predominantly acidic and nutrient-poor soils, the biome supports high primary productivity, vast stores of arable land, mineral resources, and about 20% of the global supply of surface freshwater [45,46].

This diversity of landscapes and resources is fundamental to regulating continental and global climate, especially through processes such as carbon storage, water cycling, and the so-called "flying rivers" phenomenon, which contributes to precipitation in Central and South Brazil [17,44]. Amazon's extraordinary biodiversity encompasses about 10% of all known species, including a high proportion of endemic flora and fauna [26]. Such heterogeneity underpins the selection of the study area for investigating the interplay between deforestation, water surface loss, and agricultural expansion across the biome.

2.2. Database

Initially, a comprehensive survey of Brazilian environmental policies, both historical and current, was performed. All relevant legislative acts and policy instruments were catalogued in chronological order, and their periods of validity were systematically cross-referenced with observed environmental trends during the years analyzed in this study. The political-ideological orientation of executive and legislative branches was determined using established classifications from Bolognesi et al. [47]; Power and Zucco Jr [48]; Zucco and Power [49].

For the environmental variables, we used annual land cover and land use data from MapBiomas Collection 9 (1985–2023) and MapBiomas Water, covering the entire Brazilian Amazon biome (https://brasil.mapbiomas.org/en/estatisticas/). The MapBiomas datasets provide high-resolution (30 meters) maps derived from Landsat satellite imagery, pre-processed for radiometric and atmospheric correction. The land cover classes included in this study were Water Surface, Forest (encompassing both Forest and Savanna formations), and Farming (including Pasture and Agriculture). The

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Agriculture subclass comprises temporary and perennial crops, forest plantations, and mosaics of uses. MapBiomas Water offers annual layers for surface water extent and discriminates between natural and anthropogenic water bodies. Both datasets employ spectral mixture analysis and fuzzy classification rules to enhance thematic accuracy and reduce classification uncertainties [50].

All spatial layers were standardized to a standard grid (WGS 84, EPSG:4326) for comparability. Annual totals per class were extracted, and datasets were checked for consistency; anomalous values were identified and corrected, ensuring robust temporal and spatial analysis of forest, water, and agricultural dynamics.

2.3. Data Integration

To explore the relationships among land cover variables and identify temporal patterns, we first applied Principal Component Analysis (PCA), a multivariate technique that reduces data dimensionality by transforming correlated variables into a smaller set of uncorrelated components. The analysis was based on the Pearson correlation matrix, and the suitability of the data for PCA was confirmed using Bartlett's test of sphericity – accepted when p-value < 0.05 [51–53]. We retained components with eigenvalues greater than 1, following Kaiser's criterion, ensuring that the selected components captured most of the variance in the dataset [54,55]. Factor loadings and communalities were examined to interpret the contribution of each original variable to the principal components [56].

Subsequently, K-means cluster analysis was conducted on the principal component scores to group years with similar land cover dynamics. The optimal number of clusters was determined using the Elbow method, which identifies the point at which increasing the number of clusters yields diminishing returns in explained variance [55–58]. Analyses were performed in Python (Spyder 6.0.7, Anaconda distribution), ensuring reproducibility. Both PCA and K-means clustering are well-suited to summarize multivariate environmental time series without requiring distributional assumptions or external prediction [58]. All steps were validated for statistical adequacy and robustness, providing a solid foundation for subsequent interpretation of Amazonian land-water cover trajectories.

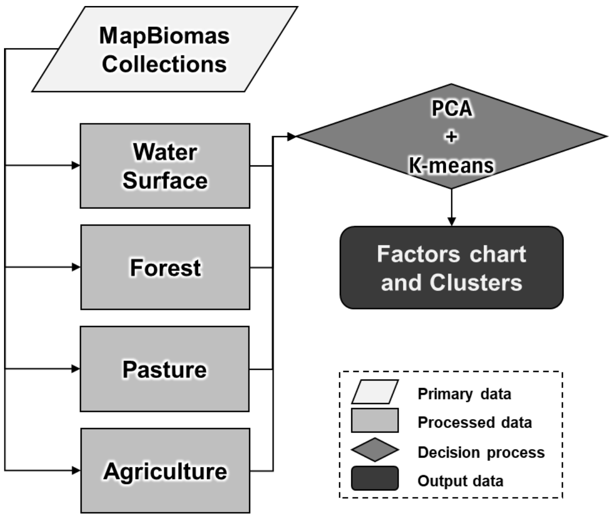

Figure 2. Flowchart summarizing the methods used in this research. PCA: Principal Component Factor Analysis; K-means: Cluster K-means Analysis.

3. Results

3.1. Contemporaneous Brazilian Legislation

Considering the analyzed period, we can observe that there is more legislation concerning environmental protection than its destruction permission. Among the ones with a positive impact,

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Law No. 7,347 of 1985 provided legal instruments for the defense of natural resources, establishing a solid foundation for the protection of forests and water. While the 1988 Federal Constitution consolidated fundamental principles for environmental protection, Law No. 7,735 of 1989 created the IBAMA, which is essential for overseeing and conserving Brazil's resources. In 1997, Law No. 9,433 established a legal framework for sustainable water management. Meanwhile, Law No. 9,985, enacted in 2000, reinforced the implementation of the National System of Conservation Units (*Sistema Nacional de Unidades de Conservação da Natureza* – SNUC), protecting both forests and water. Constitutional Amendment No. 32 of 2001 regulated and restricted the use of provisional measures, an instrument that had been frequently used previously to modify environmental legislation without broad debate, thereby reducing legal uncertainty. Decree No. 4,340 of 2002 aimed to protect significant areas of forests and water bodies, while Law No. 11,284 of 2006 promoted the sustainable use and protection of public forests. Law No. 11,516 of 2007 created the "Chico Mendes" Institute for Biodiversity Conservation (*Instituto Chico Mendes de Conservação da Biodiversidade* – ICMBio), which implements, manages, protects, inspects, monitors, and promotes federal Conservation Units (CU) of the SNUC. Law No. 12,187 of 2009 laid the groundwork for climate actions that impact water and forest resources. In 2010, Law No. 12,305 established the foundations for solid waste management, which has an indirect impact on forests and water. Finally, Law No. 14,119 of 2021, which addresses payment for environmental services, and Decree No. 11,015 of 2022 can potentially have positive impacts, but their effectiveness depends on proper implementation.

Law No. 8,171, from 1991, establishes the National Agricultural Policy, guiding Brazilian rural development with a focus on sustainable production, food security, support for family farming, and environmental protection. Law No. 8,974 of 1995 addressed biosecurity (updated by Law No. 11,105/2005), while the Forest Code (under Law No. 12,651/2012) provided amnesty for environmental crimes, such as deforestation. Law No. 13,465 of 2017 dealt with the regularization of rural and urban land. Despite that, all of them had partial or limited impacts on environmental protection. As for legislations that negatively impacted environmental protection, we have: Decree No. 99,274 from 1990 made environmental licensing more bureaucratic, with flaws in monitoring and implementation, which encouraged degradation; Law No. 9,605 of 1998 of Environmental Crimes, provides for lenient sanctions, has facilitated the impunity of offenders, making it challenging to hold major polluters accountable and allowing many environmental crimes to be resolved only with fines or alternative measures, without adequate protection or recovery of the environment. Law No. 12,973 of 2014 facilitated tax benefits without requiring environmental counterparts, favoring high-impact sectors (such as mining, agriculture, and extractive industries), indirectly contributing to ecological degradation. And the Provisional Measure No. 870, from 2019, reduced structures aimed at social participation and environmental management. More recently, two critical legislative proposals were introduced. Bill No. 2,159/2021 aims to review the general framework for environmental licensing in Brazil, potentially modifying the procedures and requirements for obtaining environmental licenses. Additionally, Bill No. 2,903/2023, known as "Marco Temporal"[2] (Time Frame), seeks to address and regulate indigenous territories, potentially favoring land grabbing. Figure 3 illustrates the representation of the majority of the National Congress at the time the legislation listed above was voted on.

[2]A Proposed Constitutional Amendment (or PEC – *Proposta de Emenda à Constituição*, in Portuguese).

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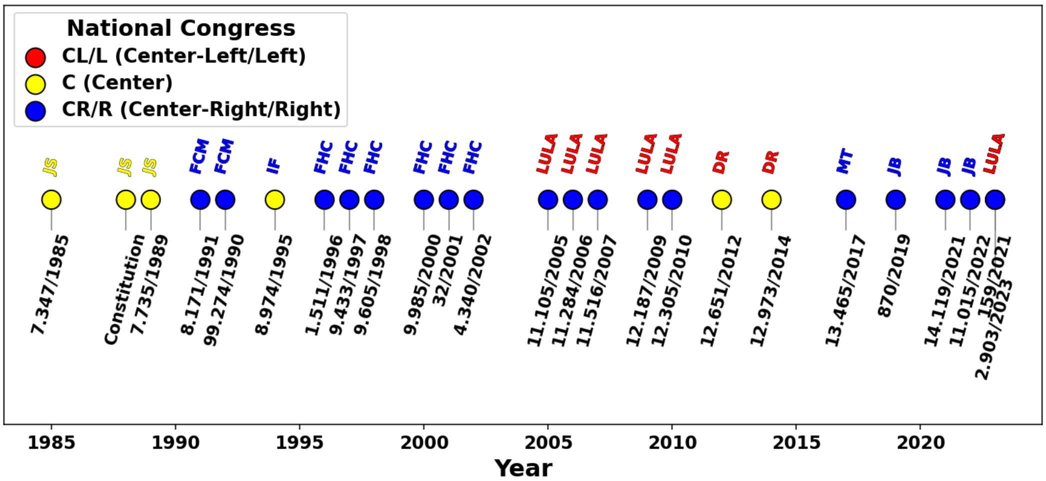

Figure 3. Timeline (1985 to 2023) of Brazilian legislation related to environmental protection. Their colored acronym or name represents the political and ideological view of the President. The colored dots represent the majority of the National Congress, where red indicates the left or center-left, yellow represents the center, and blue indicates the right or center-right. The presidents are abbreviated as follows: JS for José Sarney; FCM for Fernando Collor de Mello; IF for Itamar Franco; FHC for Fernando Henrique Cardoso; Lula for Luiz Inácio Lula da Silva; DR for Dilma Rousseff; MT for Michel Temer; and JB for Jair Bolsonaro.

Assessing the environmentalist nature, the laws in force during President José Sarney's tenure (1985, 1988, and 1989) can be considered progressive, even considering the more centrist views of both the Executive power and the National Congress. Similar to what happened during the little over 2 years of Itamar Franco, who succeeded Fernando Collor de Mello after his resignation at the end of 1992 (despite Decree No. 99,274), and with the laws approved during the two consecutive governments of Fernando Henrique Cardoso (1995-2002).

During Jair Bolsonaro's presidency (2019-2022), Congress also shared a right-wing view, which fueled a notable desire for the relaxation of environmental legislation, particularly under the leadership of then-Minister of the Environment Ricardo Salles. The most considerable discrepancy, however, can be observed during Lula's previous administration (2003-2011), his third term, since 2023; and Dilma Rousseff's presidency (2011-2016), with the Congress formed mainly by center-right and center parties, respectively. Table 1 summarizes Brazilian legislation related to environmental protection from 1985 to 2023, highlighting advances and setbacks in managing and conserving natural resources, especially forests and water.

Table 1. Environmental Legislation in Brazil from 1985 to 2023 and Its Impact on Environmental Preservation (Water and Forests). The acting presidents are abbreviated as follows: JS for José Sarney; FCM for Fernando Collor de Mello; IF for Itamar Franco; FHC for Fernando Henrique Cardoso; Lula for Luiz Inácio Lula da Silva; DR for Dilma Rousseff; MT for Michel Temer; and JB for Jair Bolsonaro. The political orientations of the presidents and the majority of the National Congress are abbreviated as L for Left, CL for Center-Left, C for Center, CR for Center-Right, and R for Right. Observation: Decree No. 23,793/1934 and Law No. 4,771/1965 (regarding the Forest Code) and Law No. 6,938/1981 are not listed here because they are outside the analyzed period in this study. The same applies to new legislation enacted after 2023 (Decree No. 12,044/2024) mentioned in the discussion.

Year	President	Presidential	National Congress	Legislation	Source
1985	JS	CR	C	Law nº 7.347/1985	http://www.planalto.gov.br/ccivil_03/leis/l7347orig.htm
1988	JS	CR	C	Federal Constitution of 1988	http://www.planalto.gov.br/ccivil_03/constituicao/constituicao.htm

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1989	JS	CR	C	Law nº 7.735/1989	http://www.planalto.gov.br/ccivil_03/leis/l7735.htm
1991	FCM	CR	CR	Law nº 8.171/1991	http://www.planalto.gov.br/ccivil_03/leis/l8171.htm
1992	FCM	CR	CR	Decree nº 99.274/1990	http://www.planalto.gov.br/ccivil_03/decreto/1990-1994/D99274.htm
1994	IF	CR	C	Law nº 8.974/1995	http://www.planalto.gov.br/ccivil_03/leis/l8974.htm
1996	FHC	C	CR	Provisional Measure nº 1.511/1996	https://www.planalto.gov.br/ccivil_03/mpv/antigas/1511.htm
1997	FHC	C	CR	Law nº 9.433/1997	http://www.planalto.gov.br/ccivil_03/leis/l9433.htm
1998	FHC	C	CR	Law nº 9.605/1998	http://www.planalto.gov.br/ccivil_03/leis/l9605.htm
2000	FHC	C	CR	Law nº 9.985/2000	http://www.planalto.gov.br/ccivil_03/leis/l9985.htm
2001	FHC	C	CR	Constitution Amendment nº 32/2001	http://www.planalto.gov.br/ccivil_03/constituicao/emendas/emc/emc32.htm
2002	FHC	C	CR	Decree nº 4.340/2002	http://www.planalto.gov.br/ccivil_03/decreto/2002/d4340.htm
2005	Lula	L	CR	Law No. 11,105/2005	https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2005/lei/l11105.htm
2006	Lula	L	CR	Law nº 11.284/2006	http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2006/lei/l11284.htm
2007	Lula	L	CR	Law nº 11.516/2007	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2007/lei/l11516.htm
2009	Lula	L	CR	Law nº 12.187/2009	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/l12187.htm)
2010	Lula	L	CR	Law nº 12.305/2010	http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm
2012	DR	L	C	Law nº 12.651/2012	http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm
2014	DR	L	C	Law nº 12.973/2014	http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2014/lei/l12973.htm
2017	MT	CR	CR	Law nº 13.465/2017	http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13465.htm
2019	JB	R	R	Provisional Measure nº 870/2019	http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2019/Mpv/mpv870.htm
2021	JB	R	R	Law nº 14.119/2021	http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2021/lei/L14119.htm
2022	JB	R	R	Decree nº 11.015/2022	http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/D11015.htm
2023	Lula	L	CR	Bill nº 2,159/2021	https://legis.senado.leg.br/sdleg-getter/documento?dm=8979282&disposition=inline
2023	Lula	L	CR	Bill nº 2.903/2023	https://legis.senado.leg.br/sdleg-getter/documento?dm=9376905&disposition=inline

3.2. Data Description and Characterization

Table 2 presents a statistical summary and description of land cover and use classes for the Amazon biome from 1985 to 2023, with all areas expressed in hectares (ha). Over this period, agricultural areas averaged approximately 2,710,000 ha (std: 2,600,000 ha), ranging from a minimum of 134,000 ha in 1985 to a maximum of 7,320,000 ha in 2023. This represents a remarkable increase of approximately 5,363% in agricultural area during the study period. Forest areas maintained a mean of roughly 311,000,000 ha (standard deviation: 15,700,000 ha), with values ranging from 287,000,000 ha in 2023 to a maximum of 338,000,000 ha in 1985, corresponding to a reduction of nearly 15% in forest area over these decades. Pasture areas showed an average of 38,700,000 ha (standard deviation: 14,100,000 ha), varying between 12,700,000 ha in 1985 and 59,100,000 ha in 2023, resulting in a total increase of approximately 365%. The water surface had a mean of 11,300,000 ha (std: 537,000 ha), with observed values ranging from 10,400,000 ha in 2016 to 12,600,000 ha in 1999, reflecting a decrease of roughly 17% between its maximum and minimum observed values.

Table 2. Statistical description of the land cover and use classes (ha) analyzed for the Amazon biome.

Stats	Agriculture	Forest	Pasture	Water surface
mean	2.71E+06	3.11E+08	3.7E+07	1.13E+07
std	2.60E+06	1.57E+07	1.41E+07	5.37E+05
min	1.34E+05	2.87E+08	1.27E+07	1.04E+07
25%	3.58E+05	2.98E+08	2.59E+07	1.09E+07
50%	1.86E+06	3.07E+08	4.45E+07	1.11E+07
75%	4.73E+06	3.25E+08	5.00E+07	1.17E+07
max	7.32E+06	3.38E+08	5.91E+07	1.26E+07

The data indicate a clear trend: forest and water surface areas decreased over the study period, while agricultural and pasture areas increased substantially. The reduction in forests, from a high of 338,000,000 ha in 1985 to lows near 287,000,000 ha in 2023 (−15%), and in water surface from 12,600,000 ha (1999) to 10,400,000 ha (2016) (−17%), appears directly related to the expansion of agriculture and pasture, with maximum values reaching 7,320,000 ha (+5,363%) and 59,100,000 ha (+365%) respectively in 2023.

Figure 4 visually summarizes the main land cover trends in the Amazon biome from 1985 to 2023. Figure 4a shows a pronounced decline in water surface area, with notably greater interannual variability than observed for forest, pasture, or agriculture. This high variability reflects the Amazon's dynamic hydrological regime, strongly influenced by seasonal, interannual, and decadal climate fluctuations, including El Niño and La Niña events [16,20,21], as well as anthropogenic factors such as deforestation, dam construction, and consequent sedimentation changes [17,18]. Meanwhile, Figure 4b documents a persistent annual reduction in forest area, attributed to ongoing deforestation and land conversion. In contrast, Figures 4c and 4d confirm a sustained yearly expansion of pasture and agricultural areas throughout the study period, highlighting significant shifts in land use across the Amazon biome.

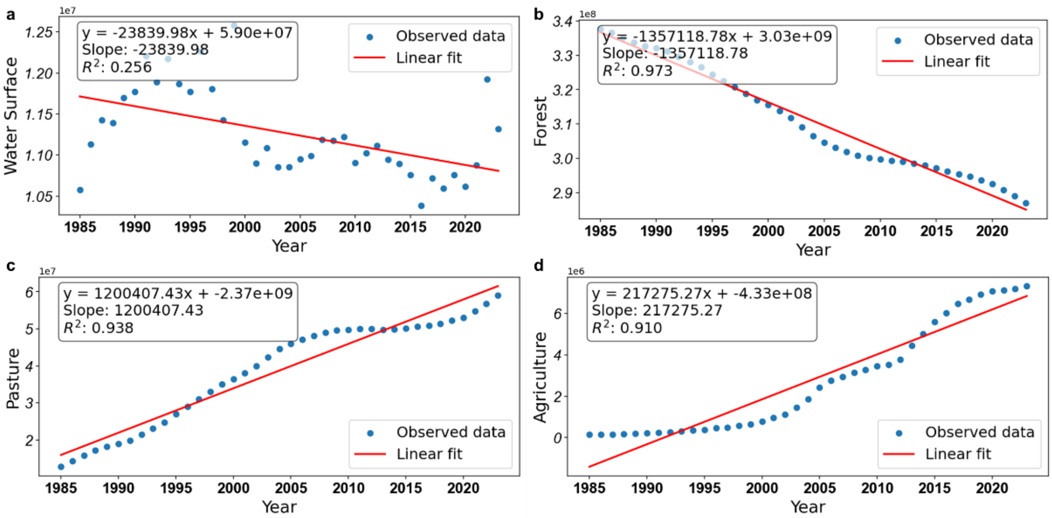

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Figure 4. Trend fit: (a) Water Surface, (b) Forest, (c) Pasture, and (d) Agriculture. The X-axis represents years and the Y-axis shows area in hectares (ha). The pronounced variability observed in water surface area reflects the Amazon's natural flood pulse regime, further influenced by climate extremes events, as well as changes in land use.

3.3. Multivariate Data Analysis

3.1.1. Principal Component Factor Analysis

The correlation matrix in Table 3 reveals statistically significant associations between the analyzed variables. The negative correlation of -0.9077 between the "Agriculture" and "Forest" classes suggests that the increase in agricultural areas is inversely related to the extent of forest areas. Similarly, "Pasture" shows a strong positive correlation (0.8625) with "Agriculture," indicating a trend that these two land use categories expand together. On the other hand, the correlation of -0.9952 between "Forest" and "Pasture" evidences a significant inverse relationship, suggesting that the increase in pasture areas is strongly associated with the reduction of forest areas. The "Water surface" presents negative correlations with "Agriculture" (-0.5425) and "Pasture" (0.5138), and a positive correlation with "Forest" (0.5308), indicating a slight tendency to preserve water surfaces in more forested areas.

Table 3. Correlation matrix.

Class	Agriculture	Forest	Pasture	Water surface
Agriculture	-	***	***	***
Forest	-0.9077	-	***	***
Pasture	0.8625	-0.9952	-	***
Water surface	-0.5425	0.5308	0.5138	-

Bartlett's test confirms the matrix's suitability for Principal Component Analysis (PCA), with a statistic of 411.4266 and a p-value of 9.7622E-86, indicating that the correlations are statistically different from zero, making PCA a viable tool for this study [55,58]. The PCA revealed that only the first factor has an eigenvalue greater than 1 (3.222261), explaining 80.56% of the total variance. Although the second factor does not meet this criterion (eigenvalue of 0.624708), it was included to increase the cumulative explained variance to 96.17% (Table 4). The factor loadings show that the first factor is strongly associated with "Agriculture" (0.938232), "Forest" (-0.976358), and "Pasture" (0.959537), while the second factor is linked to "Water Surface" (0.728948) and, to a lesser degree, to "Pasture" (0.202502) and "Forest" (-0.191562), clearly differentiating land uses. The substantial factor loading of "Water Surface" on the second factor (0.728948) highlights its distinct behavior in the dataset. Additionally, the high commonality values for all variables (0.895919 for "Agriculture", 0.989971 for "Forest", 0.961719 for "Pasture", and 0.999361 for "Water Surface") demonstrate the PCA's effectiveness in capturing the structure of the original data (Table 5).

Table 4. Eigenvalue, variance, and accumulated variance values.

Factor	Eigenvalue	Variance	Variance Accumulated
1	3.222261	0.805565	0.805565
2	0.624708	0.156177	0.961742

Table 5. Factor loadings and commonality values.

Class	Factor 1	Factor 2	commonality
Agriculture	0.938232	0.125057	0.895919
Forest	-0.976358	-0.191562	0.989971
Pasture	0.959537	0.202502	0.961719
Water surface	-0.684102	0.728948	0.999361

3.4. Cluster Analysis

Using the factors extracted from PCA, the cluster analysis considered two factors for group formation. "Factor 1" and "Factor 2" exhibit high variability between groups, with extremely low p-values of 6.8917E-03 and 2.2528E-05 for the F test, respectively, indicating the statistical significance of the formed clusters. The analysis suggests that "Factor 1" is more related to variation between groups due to differences in land use, while "Factor 2" adds nuances related to the presence of water surfaces. In this sense, the resulting clusters indicate that segmenting the study areas into distinct groups based on land use patterns and water availability is viable and statistically robust. In this context, the Elbow plot analysis (Figure 5) suggests selecting four data segment clusters. After the inflection point at four clusters, the rate of decrease in inertia becomes less pronounced, suggesting that adding more clusters beyond this point offers marginal returns in terms of additional explanation of variance in the data [55].

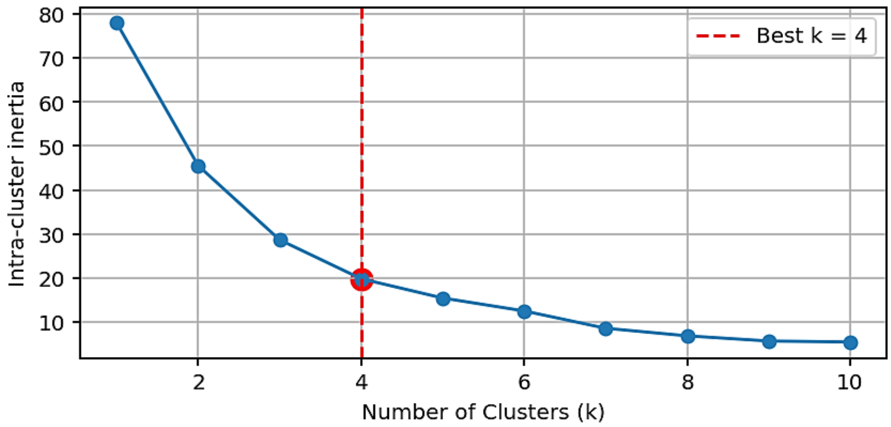

Figure 5. Elbow method for cluster number identification.

Figure 6 presents the distribution of years in the factorial space defined by the first two principal components, highlighting the association of each period with land use classes. The "Forest" and "Water Surface" vectors are positioned toward the negative side of Factor 1 (x-axis)), while "Pasture" and "Agriculture" are on the positive side, illustrating the gradient from natural to anthropogenic land uses.

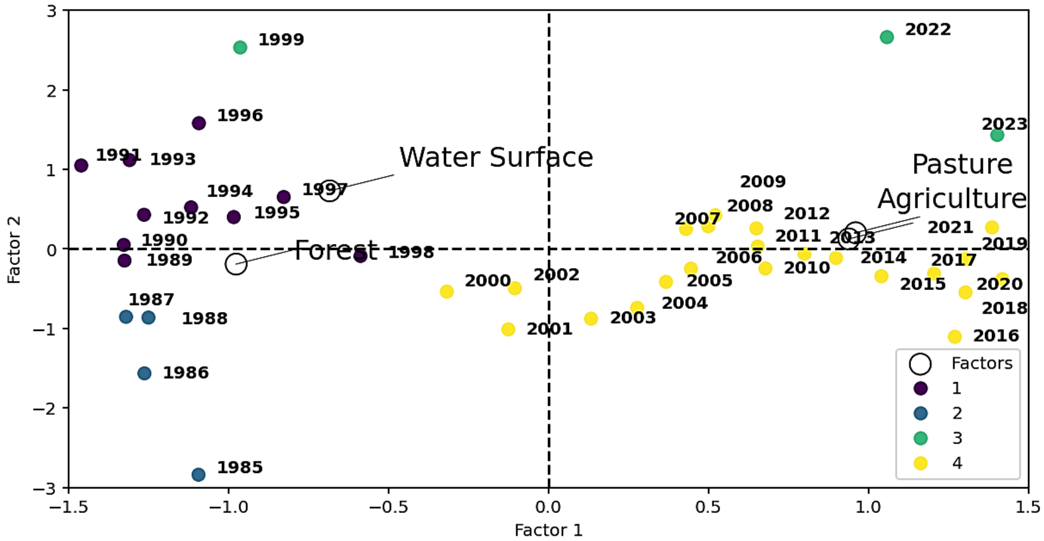

Figure 6. Chart of clusters and factors combined.

Cluster 2 (blue), corresponding to the years 1985–1988, is located in the lower left quadrant, marked by negative values for both factors. This region is associated with the preservation of forest areas and greater water surface, indicating less influence from agricultural expansion in the earliest period analyzed.

Cluster 1 (purple), which spans the years 1989–1998, is located in the left-central region of the plot, adjacent to the “Forest” and “Water Surface” vectors. These years mark a transitional period, characterized by relatively high preservation of natural areas, yet with a slight shift towards anthropogenic land uses. Notably, years such as 1996 and 1993 are associated with higher values of Factor 2 (y-axis), indicating years.

Cluster 3 (green), with the years 1999, 2022, and 2023, stands out with very high values of Factor 2, especially in 1999 and 2022. These years are outliers in the factorial space and are closely aligned with elevated “Water Surface” values. Such anomalies may be explained by climatic events like La Niña, which intensifies rainfall and thus increases water surface area in the Amazon biome, which was also influenced by La Niña events observed by the Multivariate ENSO Index (https://psl.noaa.gov/enso/mei/) [16,20,21,59–62].

Cluster 4 (yellow), spanning 2000–2021, dominates the right side of the graph, in the positive region of Factor 1, and is strongly associated with “Pasture” and “Agriculture.” This group encompasses the years when anthropogenic land uses became predominant, showing the progressive replacement of forest and water bodies by agricultural and pasture expansion. The most recent years (especially 2016–2021) confirm the intensification of this process, with a clear trend of land conversion.

Overall, Figure 6, supported by Table 2, confirms a temporal shift: areas of “Forest” and “Water Surface” have declined over the decades, while “Pasture” and “Agriculture” have expanded. The factorial structure also reveals the particularities of years marked by hydrological extremes, underscoring the dynamic interplay between climate and land use in the Amazon.

To better integrate our empirical results with the regulatory context, we compared the primary shifts in land cover and water surface with key legislative milestones. The period 1985–1988, marked by forest and water preservation, coincides with the 1988 Constitution and IBAMA’s creation. The 1989–1998 cluster reflects further policy advances, including an increase in LR area. In contrast, 2000–2021 saw rapid forest and water loss and expansion of agriculture, paralleling frequent legal changes, the 2012 Forest Code relaxation, and increased regulatory uncertainty. Accelerated deforestation and water loss in 2016–2022 align with weakened enforcement and policy rollbacks under former presidents Temer and Bolsonaro. Thus, gaps in enforcement, land regularization, and monitoring largely explain the temporal and spatial variability observed, underscoring the direct link between legislative instability and environmental degradation in the Amazon.

4. Discussion

4.1. Historical Evolution of Environmental Policies in the Amazon

Following the end of the military dictatorship, Brazil underwent significant social transformations as its political system reopened. José Sarney was the first president of the new democratic era. Still, he was only the vice president for Tancredo Neves, who was voted indirectly (not by the people) and died before he could take office.

Although environmental concerns were already addressed in its new Constitution [63], it was only the following year that the country established the IBAMA, which unified several agencies and became responsible for implementing national environmental policy [33,63]. During the 1990s, Brazil ratified international conventions, including the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC), both signed at the Earth Summit in 1992 in Rio de Janeiro, thereby consolidating the country as a leader in environmental diplomacy [33,63].

4.2. Legislative Changes, Governance, and Land-Use Dynamics

Integrating theoretical frameworks is crucial to understanding how environmental policy and governance shape ecological outcomes in the Amazon. Ostrom [64] Environmental Governance Framework emphasizes that effective governance relies not just on formal laws, but also on stakeholder engagement and strong enforcement mechanisms. Similarly, Geist and Lambin [65] show that both proximate drivers, such as agricultural expansion, and underlying institutional or economic factors, influence deforestation. In Brazil, recent legislative shifts, such as the 2012 Forest Code revision and other regulatory rollbacks, reflect both alignment and divergence with these models. Measures like the Rural Environmental Registry (RER, from the acronym in Portuguese CAR – *Cadastro Ambiental Rural*) improve transparency and monitoring, yet weakened enforcement and greater institutional uncertainty are linked to increased deforestation. Therefore, interpreting policy changes through established governance theories is key to explaining the observed patterns of forest and water loss in the Amazon biome.

Consistent with these theoretical perspectives, our findings reveal that sharp increases in agricultural and pasture expansion consistently follow periods of regulatory weakening or policy reversal, such as after the 2012 revision of the Forest Code [37,66] and following 2016, during the Temer and posterior Bolsonaro administrations [39,40]. Conversely, brief periods of legislative strengthening and increased enforcement, such as the implementation of the PPCDAm in 2004 and environmental fines in the early 2000s, are temporally associated with reduced rates of forest and water loss [67,68]. This temporal correspondence emphasizes that gaps in regulation, whether in the form of reduced LR, weak penalties, or limited enforcement, have played a decisive role in shaping land cover trajectories in the Brazilian Amazon, reinforcing the need for robust, consistent, and science-based environmental Governance [64,65,69]. The chronology of the main events related to the executive administrations and surveyed environmental legislation is detailed below.

The recent surge in global awareness of conservation and sustainable development is reflected in Brazil's environmental policy, which was in effect between 1989 and 1998. After 1992, the Brazilian government introduced the National Environment Program, aiming to integrate environmental policies with socioeconomic development, promoting sustainable management of natural resources [34]. In 1995, under the first term of Fernando Henrique Cardoso (a right-centered president), Brazil created new CU and strengthened environmental legislation. The National Environmental Policy Act was revised to include economic and fiscal incentives for preservation [70]. In 1998, the Environmental Crimes Law was enacted, imposing severe penalties for harmful activities against the environment, marking a significant advancement in environmental legislation [32,71].

During his second term, in 1999, this last law was effectively applied, and the Pilot Program for the Protection of Tropical Forests was launched to balance economic development and conservation [34,70–72], meaning that Brazil has implemented progressive environmental policies, strengthened institutions, and increased enforcement against illegal deforestation. However, in his final years as President, between 2002 and 2003, Brazilian environmental legislation reflected the tension between economic development and environmental conservation, with the National Congress having a more conservative mindset.

During Lula's first administration (2003-2010), Brazil made notable progress in conservation policies. With the help of the Legislative Houses at that time, the implementation of the PPCDAm in 2004 resulted in a significant reduction of deforestation in the Amazon, highlighting the country as a global leader in sustainability [67,68]. Some agreements contributed to the reduction of deforestation in the Amazon. The Soy Moratorium, launched in 2006 as an agreement between soy-buying companies and Civil Society Organizations, was implemented to ensure that soy produced and traded within the Amazon biome is free from deforestation occurring after 2008 [73]. In 2009, the Federal Public Prosecutor and participants in the livestock production chain signed the Term of Adjustment of Conduct (Beef TACs), aiming to prevent the purchase of cattle from properties where deforestation had occurred after 2008 [74].

Under President Dilma Rousseff's administration, from the same Labour Party as Lula, the enactment of the new Forest Code in 2012 (Law No. 12,651/2012) can be considered the most controversial milestone of the 21st century, as it relaxed forest protection rules on private properties, sparking debates about its impact on biodiversity [37].

Replacing the old Forest Code of 1965, the main setbacks of the new law involve the reduction of the LR requirement in the Amazon biome from 80% to 50% in certain cases—specifically, when the municipality has more than 50% of its territory protected by CU or Indigenous Lands (IL), or when the state has over 65% protected and an approved Ecological-Economic Zoning (ZEE), with authorization from the state environmental agency. Additionally, the law permits low-impact activities in areas of Permanent Preservation (APP), such as riverbank buffers, depending on their length and the size of the property. Decisions that were criticized for potentially encouraging deforestation [75,76]. But, worst of all, was that this law promoted the amnesty of fines applied before 2008 [5,77,78], corresponding to 88 million hectares; mainly for small producers, who constitute 90% of rural properties [37,79].

However, the updated Forest Code also introduced the mandatory RER [3,80] to restore and protect protected areas. That said, deforestation and forest degradation increased by 28% in the first year after this change in the law [66]. And despite everything, the Brazilian Forest Code is still considered extremely ambitious when compared to other similar legislation in the rest of the world [37].

An analysis of the economic results during the period with the Labour Party in office (2003-2013) indicated that the political decisions of the presidency were crucial in shaping the future Brazilian scenario, as suggested by Viola & Basso [4]. Dissatisfaction due to the lack of a forecast for necessary reforms (e.g., labor, fiscal, among others) was reflected in public discontent and the erosion of political support, culminating in the brevity of Dilma Rousseff's second term, which was interrupted by her impeachment in August 2016. Since then, there has been evident tension and consequent distancing between the Executive and Legislative branches, except for the years of Michel Temer, who took office in 2016 and remained in office until the end of 2019. In addition to a growing political polarization between the parties [48,49], which always compromises the passage of laws and the progress of government agendas.

It is a common problem in coalition presidentialism, as the Brazilian political system can be considered nowadays [49], meaning that the parliament has considerable influence on decisions. More importantly, presidential changes are sources of administrative instability and institutional vulnerability, with significant repercussions on the increase in deforestation, as observed mainly between 1995 and 2004 [81]. This is because, often, the president in power ends up negotiating some concessions in search of support in Congress, as occurred during Michel Temer's government [69], when 40% of Congress was comprised of the Agricultural Parliamentary Front, which controls agribusiness in the country [82]. These ruralists (and also mining) lobby groups defend only their own interests and seek an immediate exploratory policy.

That ends up affecting not only the Amazon but also other biomes such as the Cerrado [69], which contributes to an ecotone region of the Arc of Deforestation, between the states of Mato Grosso, Rondônia, eastern Acre, as well as southern Pará, Tocantins and Maranhão [83,84]. This region, which includes the Upper Xingu Basin [85], represents the main advance of the agricultural frontier and has been the target of deforestation over the past 50 years [7,86].

4.3. Socio-Ecological Processes and Environmental Feedbacks

In addition to wood (which is an extractive product) soybeans and beef (derived from agricultural activities) are considered commodities and are largely responsible for driving deforestation rates in the Amazon region [81]. This relationship between deforestation and extensive livestock farming has been previously indicated by studies such as Farias and Almeida [87], which examined the conversion of forests into areas for agricultural use for export between 2000 and 2010 in 782 municipalities within the Brazilian Legal Amazon area [88].

With an estimated cattle herd of 200 million heads in 2016 [89], extensive livestock farming remains a recognized source of greenhouse gas (GHG) emissions [69,82,90]. Rochedo et al. [69] divided the period up to 2017 into three, with the first period before 2005 represented by weak environmental governance; 2005 to 2011 by a decrease in the deforestation rate, and between 2012 and 2017 by the immediate result of the change in the Forest Code.

To make matters worse, there is an overlap between the loss of vegetated areas and the degradation of aquatic ecosystems, with a direct impact on aquatic biodiversity and surrounding populations [91]. This is because the local decrease in original vegetation cover (i.e., changes in land use), linked to global climate change, affects average precipitation and, consequently, the frequency and intensity of drought periods in the region, impacting both food production and hydroelectric power generation [92].

This deforestation rate is higher in areas close to rivers and roads [93], and settlements [94], which contradicts the argument that large-scale projects will aid the region's economic development [3]. Following the example of the construction of the gigantic Belo Monte hydroelectric power plant, not only does this type of project fail to achieve what was promised, but it also generates other socio-environmental conflicts in the region [95], and even caused the resignation of the then Minister of the Environment in 2008, during the discussion on environmental licensing, generating a negative impact on Brazil's image abroad [96,97].

In parallel with hydropower projects, road paving is considered important in the dynamics of land use and land cover change (LULCC), as it is part of the infrastructure needed to generate accessibility to more remote areas, as well as in the flow of agricultural products, leading to increased deforestation [98], population pressure and, consequently, environmental pressure [99]. Other threats, such as the exploitation of mineral resources, end up negatively impacting the development of the region [97], also contributing to water pollution [100], and generating deforestation of areas beyond those initially leased/licensed for such activity [101].

All this causes multiple conflicts and disputes over land, with clashes between indigenous people, *quilombolas* (quilombo communities), riverside dwellers, and rubber tappers (original and traditional communities), with the potential to generate land grabbing and subsequent use of Law No. 6969/1981, which allows the acquisition of land by adverse possession and facilitates deforestation [7], as well as arson [3] and even the use of pesticides (many of which are absurdly authorized in Brazil) [102] dispersed by aircraft, to expel the population from those places. Furthermore, civil crimes are also committed against those who fight for the preservation of the Amazon, with some emblematic cases being the deaths of rubber tapper and environmentalist Chico Mendes (1988), Sister Dorothy Stang (2005) [5] and just over 3 years ago, the murder of journalist Dom Phillips and indigenous activist Bruno Pereira, in 2022.

4.4. Policy Implications and Conservation Challenges

Thus, it is notable that, starting in 2016, during the administrations of Michel Temer and Jair Bolsonaro, environmental policies weakened, marked by austerity measures and reduced resources for environmental enforcement [40]. The Bolsonaro years (2019-2022) were particularly disastrous, especially during the COVID-19 pandemic, with increased deforestation and forest fires due to deregulation and the promotion of agricultural activities in protected areas [103–106]. The reversal of protection policies and the prioritization of economic growth over environmental conservation generated domestic and international criticism, highlighting a setback in previous achievements [38–40].

Former President Bolsonaro not only encouraged the devaluation of regulatory agencies, such as IBAMA and ICMBio, during his government, through cuts, but also dismissed scientist Ricardo Galvão from the board of the INPE, which is the leading institute for monitoring deforestation in Brazil [107] – but also weakened legislation and increased the amount of pesticides permitted in the country [7,102].

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Recently, two Bills have been the focus of debate. The first, Bill No. 2,159/2021, received the nickname "Devastation Bill" for simplifying environmental licensing procedures, eliminating the requirement for a license for some "lower impact" activities, while creating a self-declaration instrument for other ventures, representing a colossal setback in environmental protection policy. Although it has already been approved by both the Senate and the Chamber of Deputies, President Lula vetoed some of the most controversial sections of the Bill, further exacerbating the disparity of interests between the legislative and executive branches. The second deals with the recognition of IL that existed before the enactment of the 1988 Constitution, known as the "Time Frame," by Bill No. 2,903/2023 [108,109] and is currently under discussion in the Supreme Court.

Such demarcations were suspended during the Temer period, at the same time that land grabbing in the Amazon was tolerated, as one of the government's maneuvers in its search for political support [69]. Evidence suggests that the demarcation of IL provides greater protection for forests [93], which helps reduce deforestation, even if it is discreet [110,111]. Contrary to what many propagate, that IL are empty spaces without use, these territories are areas belonging to the Union, and for the sole use of traditional communities located there to maintain their subsistence (article 231 of the Constitution) [111], and where commercial activities and those carried out by non-indigenous people (Such as monocultures, logging, and mining) are prohibited. In general, indigenous communities are considered effective land managers, helping to combat deforestation and, consequently, climate change [112,113]. In fact, among the APPs, IL was the most efficient in reducing deforestation between 2005 and 2009 [114].

Furthermore, according to a recent report from the non-governmental organization Climate Observatory [115] there are a total of 46 projects considered worrying, related to environmental legislation (among 100 proposals analyzed, including Bills No. 2,159 and 2,903) and which can enter processing in the Congress at any time, justifying the importance of public monitoring of the country's political changes.

4.5. Ecological Feedbacks, Socio-Environmental Risks, and Future Pathways

It is important to note that in 2022, despite the intense and disastrous environmental mismanagement by former President Jair Bolsonaro, the increase in water surface area in the region was solely and exclusively caused by the global climate phenomenon La Niña [16,21,59] – as observed in Cluster 3 of Figure 6. Fire is also an essential factor to be considered in the changes that have occurred in the Amazon basin in recent times [18,116], resulting in considerable water stress, and extreme events considerably increase forest fires, with intense episodes in El Niño years (1997, 2009, 2015) [93].

Together, all these pressures on the Amazon biome led to the loss of biodiversity due to habitat reduction and ecosystem services [117]. The most significant risk is the irreversible loss of forest, resulting in a transition to ecosystems dominated by savanna-like vegetation[3]. In such scenarios, this substitution could potentially cause a 44% reduction in average annual rainfall and an increase of up to 69% in the length of the dry season [3,118,119], which is accompanied by a decrease in human well-being, likely due to unplanned urbanization and inadequate infrastructure. Such consequences are the result of the absence of decisions based on scientific evidence (Science-based decision), often completely ignoring them [120], which is strongly linked to the economic and financial interests of a few groups in Brazilian society, represented in the Legislative branch.

This interface between the adopted policy and the observed consequences for the environment was previously addressed by Monteiro et al. [3] while Moreira-Dantas and Soder [121] had already evaluated the link between weak institutional governance (and the perception of corruption) in several countries and the increase in deforestation rates. Therefore, Zimbres et al. [112] reinforce the recommendation for more present environmental legislation, which requires political will, unlike

[3]In this regard, we were careful not to use the term "savannization", as requested by the Institute of Society, Population and Nature (ISPN) (https://ispn.org.br/site/wp-content/uploads/2020/10/Nota-Savanizacao.pdf).

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what occurred in the Bolsonaro government (2018-2022), through the strengthening of committees in both the Chamber of Deputies and the Federal Senate, with the help of adequate scientific advice, to avoid isolation with an exclusively political bias in decisions that affect the entire Brazilian territory [120]. And with an impact that is often regional and even global, as is the case in the Amazon, since our climate security is closely linked to the protection of this biome [122]. Monteiro et al. [3], Moreira-Dantas and Söder [121] had already assessed the link between weak institutional governance (and the perception of corruption) in several countries and the increase in deforestation rates. Therefore, Zimbres et al. [112] reinforce the recommendation for more present environmental legislation, which requires political will, unlike what occurred in the Bolsonaro government (2018-2022), through the strengthening of committees in both the Chamber of Deputies and the Federal Senate, with the help of adequate scientific advice, to avoid isolation with an exclusively political bias in decisions that affect the entire Brazilian territory [120]. And with an impact that is often regional and even global, as is the case in the Amazon, since our climate security is closely linked to the protection of this biome [122].

Tax incentives should be considered more seriously as alternatives to combat deforestation in the Amazon, such as the 'Terra Legal' Program, which was launched in 2009 during the second Lula administration and legalized land registers [123]. Other PES in their various forms, as provided for in Law No. 14,119/2021 (sanctioned by then-President Jair Bolsonaro), need to become a reality. In addition to strengthening monitoring to combat deforestation in Brazilian territory, which in no way hinders economic growth [124].

As pointed out by Nobre, Nobre [125], Nobre [126] and Strand et al. [79]; there are alternatives for sustainable socioeconomic development in this region that respect environmental conservation, taking advantage of the various products and resources the biome provides, such as timber, minerals, molecules for cosmetic and pharmaceutical compounds, and, of course, water (for energy and supply) and food from agroforestry systems. Including the practice of more efficient and lower-impact livestock farming [78], but mainly maintaining the standing forest [118] and reversing the profits obtained back into its protection, encouraging regional entrepreneurship [126], in the direction of what is described in the recent National Bioeconomy Strategy (Decree No. 12,044/2024).

Without a doubt, Brazil is at the center of the fight against the climate emergency [127]. Therefore, it is essential to emphasize that firmer actions are necessary to ensure our sovereignty, while also serving as an example for other countries to achieve the goals set out in the Paris Agreement through sustainable governance.

5. Conclusions

The study examined the relationship between water surface loss and deforestation in the Brazilian Amazon, focusing on the impact of agricultural expansion and legislative policies from 1985 to 2023. The results indicate an average annual reduction of 57,900 hectares (approximately 579 km^2) in water surface area, representing a total decrease of about 17% (from a maximum of 12,600,000 hectares in 1999 to a minimum of 10,400,000 hectares in 2016). Forest cover declined from a maximum of 338,000,000 hectares to about 287,000,000 hectares, corresponding to a reduction of nearly 15% over the period. In contrast, agricultural areas increased by approximately 5,363% (from 134,000 hectares in 1985 to 7,320,000 hectares in 2023), and pasture areas expanded by 365% (from 12,700,000 hectares to 59,100,000 hectares) over the same period. The multivariate analyses reveal a significant negative correlation between the "Water Surface" and "Forest" classes, which decrease, and the "Pasture" and "Agriculture" classes, which increase.

The research also highlights the role of public policies in environmental protection, recognizing advances such as the creation of IBAMA and the development of legal frameworks for water resource management by Central and Left-leaning governments. However, the 2012 Forest Code, an initiative primarily driven by the decisions of progressive left-leaning legislative houses, is considered controversial due to the relaxation of forest protection rules, which directly resulted in a marked increase in deforestation rates. Additionally, significant setbacks in environmental regulations, particularly regarding forest protection, are attributed to Center-Right and Right-leaning governments, which have prioritized immediate economic interests over environmental sustainability., emphasizing the importance of the public monitoring of what is discussed and voted on by our leaders.

Despite the high accuracy standards of the data from the MapBiomas Project Collection 9, the present study presents some limitations and uncertainties, as the analysis focused only on Brazil, even though the Amazon biome spans other South American countries. Future work can explore comparative analyses between those and neighboring biomes, further evaluating the impact of climate change and contributing to more effective analysis methodologies, as well as public policies that reconcile environmental conservation and sustainable economic development in the region.

A self-recognized observed limitation of this study is its biome-wide analytical scale, which, while effective for detecting major temporal transitions and cumulative effects of national policies, may mask significant sub-regional differences in land-use change and policy enforcement across the Amazon. The region encompasses diverse ecological zones, land-use histories, and socio-political realities, such as the highly dynamic "Arc of Deforestation," protected areas, and indigenous lands, each with distinct trajectories and pressures. Future research should apply similar or more advanced analytical frameworks at finer spatial resolutions (e.g., state, municipality, protected areas, or settlement level), incorporating enforcement data, local governance, and cross-scale interactions. Such approaches will be essential for unraveling the complexity of land-use trajectories and policy outcomes within the Amazon, ultimately supporting more targeted and effective conservation and development strategies.

That said, 25 years after the Earth Summit, the Amazon is once again the focus of global attention, as it will be the stage for the next Conference of the Parties on climate change (COP 30) in Belém. According to Marina Silva's speech, "man legislates, but nature does not assimilate" at the same speed as changes in the law, referring to the fact that the interests of the Legislative Branch often correspond to more urgent economic interests, and do not consider the legacy beyond our lifetime.

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References

1. Drummond, J.A. O Jardim Dentro Da Máquina: Breve História Ambiental Da Floresta Da Tijuca. *Revista Estudos Históricos* **1988**, *1*, 276–298.

2. Farias, P.J.L. Brazil: The Evolution of the Law and Politics of Water. *The evolution of the law and politics of water* **2009**, 69–86.
3. Monteiro, M.S.A.; Seixas, S.R. da C.; Vieira, S.A. The Politics of Amazonian Deforestation: Environmental Policy and Climate Change Knowledge. *Wiley Interdiscip Rev Clim Change* **2014**, *5*, 689–701.
4. Viola, E.; Basso, L. Amazonian Policy and Politics, 2003-13: Deforestation, Hydropower and Biofuels. *NOREF-Norwegian Peacebuilding Resource Centre Report* **2014**.
5. Boekhout van Solinge, T. Chapter 12.3 - Deforestation in the Brazilian Amazon. In *Biological and Environmental Hazards, Risks, and Disasters*; Shroder, J.F., Sivanpillai, R., Eds.; Academic Press: Boston, 2016; pp. 373–395 ISBN 978-0-12-394847-2.
6. Jusys, T. Fundamental Causes and Spatial Heterogeneity of Deforestation in Legal Amazon. *Applied Geography* **2016**, *75*, 188–199.
7. de Paula Pereira, A.S.A.; Dos Santos, V.J.; do Carmo Alves, S.; e Silva, A.A.; Da Silva, C.G.; Calijuri, M.L. Contribution of Rural Settlements to the Deforestation Dynamics in the Legal Amazon. *Land use policy* **2022**, *115*, 106039.
8. Hänggli, A.; Levy, S.A.; Armenteras, D.; Bovolo, C.I.; Brandão, J.; Rueda, X.; Garrett, R.D. A Systematic Comparison of Deforestation Drivers and Policy Effectiveness across the Amazon Biome. *Environmental Research Letters* **2023**, *18*, 073001.
9. de Almeida, C.A.; Perez, L.P.; Reis, M.S.; Camilotti, V.L.; Messias, C.G.; dos Santos Monteiro, E.C.; Pinheiro, T.F.; Pinto, J.F.S.K.C.; de Souza Soler, L.; Vinhas, L. Monitoramento Oficial Da Vegetação Nativa Brasileira Por Imagens de Satélite: O Programa BiomasBR e Os Sistemas Prodes, Deter e TerraClass. *Cadernos de Astronomia* **2025**, *6*, 23–38.
10. Fearnside, P.M. Amazon Forest Maintenance as a Source of Environmental Services. *An Acad Bras Cienc* **2008**, *80*, 101–114.
11. Fujisaki, K.; Perrin, A.; Desjardins, T.; Bernoux, M.; Balbino, L.C.; Brossard, M. From Forest to Cropland and Pasture Systems: A Critical Review of Soil Organic Carbon Stocks Changes in Amazonia. *Glob Chang Biol* **2015**, *21*, 2773–2786.
12. Boulton, C.A.; Lenton, T.M.; Boers, N. Pronounced Loss of Amazon Rainforest Resilience since the Early 2000s. *Nat Clim Chang* **2022**, *12*, 271–278.
13. Nobre, C.A.; Sellers, P.J.; Shukla, J. Amazonian Deforestation and Regional Climate Change. *J Clim* **1991**, *4*, 957–988.
14. Goulding, M. *The Fishes and the Forest: Explorations in Amazonian Natural History*; Univ of California Press, 1980; ISBN 0520041313.
15. Fearnside, P.M. The Intrinsic Value of Amazon Biodiversity. *Biodivers Conserv* **2021**, *30*, 1199–1202.
16. Marengo, J.A.; Espinoza, J.C. Extreme Seasonal Droughts and Floods in Amazonia: Causes, Trends and Impacts. *International Journal of Climatology* **2016**, *36*.
17. Gatti, L. V; Cunha, C.L.; Marani, L.; Cassol, H.L.G.; Messias, C.G.; Arai, E.; Denning, A.S.; Soler, L.S.; Almeida, C.; Setzer, A. Increased Amazon Carbon Emissions Mainly from Decline in Law Enforcement. *Nature* **2023**, *621*, 318–323.
18. Davidson, E.A.; de Araújo, A.C.; Artaxo, P.; Balch, J.K.; Brown, I.F.; C. Bustamante, M.M.; Coe, M.T.; DeFries, R.S.; Keller, M.; Longo, M. The Amazon Basin in Transition. *Nature* **2012**, *481*, 321–328.
19. Lovejoy, T.E.; Nobre, C. Amazon Tipping Point: Last Chance for Action. *Sci Adv* 2019, *5*, eaba2949.
20. Marengo, J.A.; Tomasella, J.; Alves, L.M.; Soares, W.R.; Rodriguez, D.A. The Drought of 2010 in the Context of Historical Droughts in the Amazon Region. *Geophys Res Lett* **2011**, *38*.
21. Nobre, C.A.; Marengo, J.A.; Seluchi, M.E.; Cuartas, L.A.; Alves, L.M. Some Characteristics and Impacts of the Drought and Water Crisis in Southeastern Brazil during 2014 and 2015. *J Water Resour Prot* **2016**, *08*, 252–262, doi:10.4236/jwarp.2016.82022.
22. Marengo, J.A.; Williams, E.R.; Alves, L.M.; Soares, W.R.; Rodriguez, D.A. Extreme Seasonal Climate Variations in the Amazon Basin: Droughts and Floods. *Interactions between biosphere, atmosphere and human land use in the Amazon Basin* **2016**, 55–76.
23. Nobre, C.A.; Borma, L.D.S. 'Tipping Points' for the Amazon Forest. *Curr Opin Environ Sustain* **2009**, *1*, 28–36.

24. Bochow, N.; Boers, N. The South American Monsoon Approaches a Critical Transition in Response to Deforestation. *Sci Adv* **2023**, *9*, eadd9973.
25. Nepstad, D.C.; Stickler, C.M.; Filho, B.S.-; Merry, F. Interactions among Amazon Land Use, Forests and Climate: Prospects for a near-Term Forest Tipping Point. *Philosophical transactions of the royal society B: biological sciences* **2008**, *363*, 1737–1746.
26. Laurance, W.F.; Lovejoy, T.E.; Vasconcelos, H.L.; Bruna, E.M.; Didham, R.K.; Stouffer, P.C.; Gascon, C.; Bierregaard, R.O.; Laurance, S.G.; Sampaio, E. Ecosystem Decay of Amazonian Forest Fragments: A 22-year Investigation. *Conservation biology* **2002**, *16*, 605–618.
27. Messias, C.G.; Silva, D.E.; da Silva, M.B.; de Lima, T.C.; de Almeida, C.A. Análise Das Taxas de Desmatamento e Seus Fatores Associados Na Amazônia Legal Brasileira Nas Últimas Três Décadas/Analysis of Deforestation Rates and Their Drivers in the Brazilian Legal Amazon during the Last Three Decades. *Ra'e Ga* **2021**, *52*, 18–42.
28. Walker, W.S.; Gorelik, S.R.; Baccini, A.; Aragon-Osejo, J.L.; Josse, C.; Meyer, C.; Macedo, M.N.; Augusto, C.; Rios, S.; Katan, T. The Role of Forest Conversion, Degradation, and Disturbance in the Carbon Dynamics of Amazon Indigenous Territories and Protected Areas. *Proceedings of the National Academy of Sciences* **2020**, *117*, 3015–3025.
29. Drummond, J.; Barros-Platiau, A.F. Brazilian Environmental Laws and Policies, 1934–2002: A Critical Overview. *Law Policy* **2006**, *28*, 83–108.
30. Sá, M.R. A Ferro e Fogo: A História e a Devastação Da Mata Atlântica Brasileira. *Hist Cienc Saude Manguinhos* **1996**, *3*, 558–559.
31. Rajão, R.G.L.; Del Giudice, R.R.; Van der Hoff, R.; de Carvalho, E.B. *Uma Breve História Da Legislação Florestal Brasileira: Contém a Lei Nº 12.651, de 2012, Com Comentários Críticos Acerca Da Aplicação de Seus Artigos*; Universidade Federal de Minas Gerais, 2021; ISBN 6587095038.
32. de Moura, A.M.M. Environment Policy and Governance in Brazil: Challenges and Prospects. *Brazil in the Anthropocene* **2016**, 321–342.
33. Hochstetler, K.; Keck, M.E. *Greening Brazil: Environmental Activism in State and Society*; Duke University Press, 2007; ISBN 0822340313.
34. Viola, E.J. The Environmental Movement in Brazil: Institutionalization, Sustainable Development, and Crisis of Governance since 1987. In *Latin American environmental policy in international perspective*; Routledge, 1997; pp. 88–110 ISBN 0429039182.
35. Brasil *Medida Provisória Nº 1.511 de 25 de Julho de 1996*; Brasília, Brasil, 1996;
36. West, T.A.P.; Fearnside, P.M. Brazil's Conservation Reform and the Reduction of Deforestation in Amazonia. *Land use policy* **2021**, *100*, 105072.
37. Soares-Filho, B.; Rajão, R.; Macedo, M.; Carneiro, A.; Costa, W.; Coe, M.; Rodrigues, H.; Alencar, A. Cracking Brazil's Forest Code. *Science (1979)* **2014**, *344*, 363–364.
38. Vale, M.M.; Berenguer, E.; de Menezes, M.A.; de Castro, E.B.V.; de Siqueira, L.P.; Rita de Cássia, Q.P. The COVID-19 Pandemic as an Opportunity to Weaken Environmental Protection in Brazil. *Biol Conserv* **2021**, *255*, 108994.
39. Ferrante, L.; Fearnside, P.M. Brazil's New President and 'Ruralists' Threaten Amazonia's Environment, Traditional Peoples and the Global Climate. *Environ Conserv* **2019**, *46*, 261–263.
40. Barlow, J.; Berenguer, E.; Carmenta, R.; França, F. Clarifying Amazonia's Burning Crisis. *Glob Chang Biol* **2020**, *26*, 319–321.
41. Marengo, J.A. Future Climate Change Scenarios and Their Application for Studies of Impacts, Vulnerability, and Adaptation in Brazil. *Adaptación al cambio climático y servicios ecosistémicos en América Latina* **2010**, 23.
42. Messias, C.G.; de Almeida, C.A.; Silva, D.E.; Soler, L.S.; Maurano, L.E.; Camilotti, V.L.; Alves, F.C.; da Silva, L.J.; Reis, M.S.; de Lima, T.C. Unaccounted for Nonforest Vegetation Loss in the Brazilian Amazon. *Commun Earth Environ* **2024**, *5*, 451.
43. Ab'Sáber, A.N. *Os Domínios de Natureza No Brasil: Potencialidades Paisagísticas*; Ateliê editorial, 2003; Vol. 1; ISBN 8574800996.

 doi:10.20944/preprints202508.1552.v1

44. Marengo, J.A. On the Hydrological Cycle of the Amazon Basin: A Historical Review and Current State-of-the-Art. *Revista brasileira de meteorologia* **2006**, *21*, 1–19.
45. Lemos, A.L.F.; Silva, J. de A. Desmatamento Na Amazônia Legal: Evolução, Causas, Monitoramento e Possibilidades de Mitigação Através Do Fundo Amazônia. *Floresta e Ambiente* **2011**, *18*, 98–108.
46. Margulis, S. *Causes of Deforestation of the Brazilian Amazon*; World Bank Publications, 2004; Vol. 22; ISBN 0821356917.
47. Bolognesi, B.; Ribeiro, E.; Codato, A. A New Ideological Classification of Brazilian Political Parties. *Dados* **2022**, *66*, e20210164.
48. Power, T.J.; Zucco Jr, C. Estimating Ideology of Brazilian Legislative Parties, 1990–2005: A Research Communication. *Lat Am Res Rev* **2009**, *44*, 218–246.
49. Zucco, C.; Power, T.J. The Ideology of Brazilian Parties and Presidents: A Research Note on Coalitional Presidentialism under Stress. *Lat Am Polit Soc* **2024**, *66*, 178–188.
50. Souza, C.M.; Shimbo, J.Z.; Rosa, M.R.; Parente, L.L.; Rosa, E.R.; Vélez-martin, E. Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Data Archive and Google Earth Engine. *Unpublished* **2019**.
51. Field, A.; Miles, J.; Field, Z. Discovering Statistics Using R (2012). *Great Britain: Sage Publications, Ltd.* **2012**, *958*.
52. Field, A. *Descobrindo a Estatística Usando o SPSS-5*; Penso Editora, 2009; ISBN 8584292012.
53. Field, A. *Discovering Statistics Using IBM SPSS Statistics*; Sage publications limited, 2024; ISBN 1529668700.
54. Stevens, J.P. *Applied Multivariate Statistics for the Social Sciences*; Routledge, 2012; ISBN 1136910697.
55. Fávero, L.; Fávero, P. *Análise de Dados: Técnicas Multivariadas Exploratórias Com SPSS e STATA*; Elsevier Brasil: Rio de Janeiro, RJ, Brasil, 2017; ISBN 8535280669.
56. Fávero, L.P.L.; Belfiore, P.P.; Silva, F.L. da; Chan, B.L.P.P.-R. de J. *Análise de Dados: Modelagem Multivariada Para Tomada de Decisões*; Elsevier: Rio de Janeiro, RJ, Brasil, 2009;
57. Casella, G.; Fienberg, S.; Olkin, I. Springer Texts in Statistics. *Design (Vol* **2006**.
58. Fávero, L.P.; Belfiore, P. *Manual de Análise de Dados: Estatística e Modelagem Multivariada Com Excel®, SPSS® e Stata®*; Elsevier: Rio de Janeiro, RJ, Brasil, 2017;
59. Marengo, J.A.; Tomasella, J.; Soares, W.R.; Alves, L.M.; Nobre, C.A. Extreme Climatic Events in the Amazon Basin: Climatological and Hydrological Context of Recent Floods. *Theor Appl Climatol* **2012**, *107*, 73–85.
60. Wolter, K.; Timlin, M.S. El Niño/Southern Oscillation Behaviour since 1871 as Diagnosed in an Extended Multivariate ENSO Index (MEI. Ext). *International Journal of Climatology* **2011**, *31*, 1074–1087.
61. Kobayashi, S.; Ota, Y.; Harada, Y.; Ebita, A.; Moriya, M.; Onoda, H.; Onogi, K.; Kamahori, H.; Kobayashi, C.; Endo, H. The JRA-55 Reanalysis: General Specifications and Basic Characteristics. *Journal of the Meteorological Society of Japan. Ser. II* **2015**, *93*, 5–48.
62. Wolter, K. Monitoring ENSO in COADS with a Seasonally Adjusted Principal Component Index. In Proceedings of the Proc. of the 17th Climate Diagnostics Workshop, 1993; 1993.
63. O'neill, K. *The Environment and International Relations*; Cambridge University Press, 2017; ISBN 1316943003.
64. Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science (1979)* **2009**, *325*, 419–422.
65. Geist, H.J.; Lambin, E.F. Proximate Causes and Underlying Driving Forces of Tropical Deforestation: Tropical Forests Are Disappearing as the Result of Many Pressures, Both Local and Regional, Acting in Various Combinations in Different Geographical Locations. *Bioscience* **2002**, *52*, 143–150.
66. Arima, E.Y.; Barreto, P.; Araújo, E.; Soares-Filho, B. Public Policies Can Reduce Tropical Deforestation: Lessons and Challenges from Brazil. *Land use policy* **2014**, *41*, 465–473.
67. Nepstad, D.; McGrath, D.; Stickler, C.; Alencar, A.; Azevedo, A.; Swette, B.; Bezerra, T.; DiGiano, M.; Shimada, J.; Seroa da Motta, R. Slowing Amazon Deforestation through Public Policy and Interventions in Beef and Soy Supply Chains. *Science (1979)* **2014**, *344*, 1118–1123.
68. Franchini, M. Climate Change Politics in Latin America and the Caribbean. In *Oxford Research Encyclopedia of Politics*; 2021.

69. Rochedo, P.R.R.; Soares-Filho, B.; Schaeffer, R.; Viola, E.; Szklo, A.; Lucena, A.F.P.; Koberle, A.; Davis, J.L.; Rajão, R.; Rathmann, R. The Threat of Political Bargaining to Climate Mitigation in Brazil. *Nat Clim Chang* **2018**, *8*, 695–698.
70. Young, C.E.F. Financial Mechanisms for Conservation in Brazil. *Conservation Biology* **2005**, *19*, 756–761.
71. Marchesan, A.M.M.; Steigleder, A.M. *Crimes Ambientais Comentarios a Lei 9.605/98*; Livraria do Advogado Editora, 2021; ISBN 8573501278.
72. Neves, E.M.S.C. Mudança, Desmonte de Políticas e Defesa Do Meio Ambiente No Brasil. *Sustainability in Debate* **2023**, *14*, 26–57.
73. Amaral, D.F.; de Souza Ferreira Filho, J.B.; Chagas, A.L.S.; Adami, M. Expansion of Soybean Farming into Deforested Areas in the Amazon Biome: The Role and Impact of the Soy Moratorium. *Sustain Sci* **2021**, *16*, 1295–1312.
74. Rodrigues Junior, U.J.; Dziedzic, M. The Water Footprint of Beef Cattle in the Amazon Region, Brazil. *Ciência Rural* **2021**, *51*, 20190294.
75. Metzger, J.P.; Bustamante, M.M.C.; Ferreira, J.; Fernandes, G.W.; Librán-Embid, F.; Pillar, V.D.; Prist, P.R.; Rodrigues, R.R.; Vieira, I.C.G.; Overbeck, G.E. Why Brazil Needs Its Legal Reserves. *Perspect Ecol Conserv* **2019**, *17*, 91–103.
76. Chiavari, J.; Lopes, C.L.; de Alcantara Machado, L. The Brazilian Forest Code: The Challenges of Legal Implementation. In *Sustainability Challenges of Brazilian Agriculture: Governance, Inclusion, and Innovation*; Springer, 2023; pp. 295–314.
77. Santiago, T.M.O.; Caviglia-Harris, J.; de Rezende, J.L.P. Carrots, Sticks and the Brazilian Forest Code: The Promising Response of Small Landowners in the Amazon. *J For Econ* **2018**, *30*, 38–51.
78. de Azevedo Junior, W.C.; Rodrigues, M.; Silva, D.C.C. Does Agricultural Efficiency Contribute to Slowdown of Deforestation in the Brazilian Legal Amazon? *J Nat Conserv* **2022**, *65*, 126092.
79. Strand, J.; Soares-Filho, B.; Costa, M.H.; Oliveira, U.; Ribeiro, S.C.; Pires, G.F.; Oliveira, A.; Rajão, R.; May, P.; Van Der Hoff, R. Spatially Explicit Valuation of the Brazilian Amazon Forest's Ecosystem Services. *Nat Sustain* **2018**, *1*, 657–664.
80. Azevedo, A.A.; Rajão, R.; Costa, M.A.; Stabile, M.C.C.; Macedo, M.N.; Dos Reis, T.N.P.; Alencar, A.; Soares-Filho, B.S.; Pacheco, R. Limits of Brazil's Forest Code as a Means to End Illegal Deforestation. *Proceedings of the National Academy of Sciences* **2017**, *114*, 7653–7658.
81. Rodrigues-Filho, S.; Verburg, R.; Bursztyn, M.; Lindoso, D.; Debortoli, N.; Vilhena, A.M.G. Election-Driven Weakening of Deforestation Control in the Brazilian Amazon. *Land use policy* **2015**, *43*, 111–118.
82. Pereira, E.J. de A.L.; de Santana Ribeiro, L.C.; da Silva Freitas, L.F.; de Barros Pereira, H.B. Brazilian Policy and Agribusiness Damage the Amazon Rainforest. *Land use policy* **2020**, *92*, 104491.
83. Becker, B.K. *Amazônia: Geopolítica Na Virada Do III Milênio*; Editora Garamond, 2004; ISBN 8576170426.
84. Becker, B.K. Geopolítica Da Amazônia. *Estudos avançados* **2005**, *19*, 71–86.
85. Garcia, A.S.; de FN Vilela, V.M.; Rizzo, R.; West, P.; Gerber, J.S.; Engstrom, P.M.; Ballester, M.V.R. Assessing Land Use/Cover Dynamics and Exploring Drivers in the Amazon's Arc of Deforestation through a Hierarchical, Multi-Scale and Multi-Temporal Classification Approach. *Remote Sens Appl* **2019**, *15*, 100233.
86. Cavalcante, R.B.L.; Pontes, P.R.M.; Souza-Filho, P.W.M.; De Souza, E.B. Opposite Effects of Climate and Land Use Changes on the Annual Water Balance in the Amazon Arc of Deforestation. *Water Resour Res* **2019**, *55*, 3092–3106.
87. Faria, W.R.; Almeida, A.N. Relationship between Openness to Trade and Deforestation: Empirical Evidence from the Brazilian Amazon. *Ecological Economics* **2016**, *121*, 85–97.
88. França, F.; Solar, R.; Lees, A.C.; Martins, L.P.; Berenguer, E.; Barlow, J. Reassessing the Role of Cattle and Pasture in Brazil's Deforestation: A Response to "Fire, Deforestation, and Livestock: When the Smoke Clears." *Land use policy* **2021**, *108*, 105195.
89. Cardoso, A.S.; Berndt, A.; Leytem, A.; Alves, B.J.R.; de Carvalho, I. das N.O.; de Barros Soares, L.H.; Urquiaga, S.; Boddey, R.M. Impact of the Intensification of Beef Production in Brazil on Greenhouse Gas Emissions and Land Use. *Agric Syst* **2016**, *143*, 86–96.
90. Siqueira, T.T.S.; Duru, M. Economics and Environmental Performance Issues of a Typical Amazonian Beef Farm: A Case Study. *J Clean Prod* **2016**, *112*, 2485–2494.

 doi:10.20944/preprints202508.1552.v1

91. Fugère, V.; Nyboer, E.A.; Bleecker, J.C.; Chapman, L.J. Impacts of Forest Loss on Inland Waters: Identifying Critical Research Zones Based on Deforestation Rates, Aquatic Ecosystem Services, and Past Research Effort. *Biol Conserv* **2016**, *201*, 277–283.
92. Bottino, M.J.; Nobre, P.; Giarolla, E.; da Silva Junior, M.B.; Capistrano, V.B.; Malagutti, M.; Tamaoki, J.N.; De Oliveira, B.F.A.; Nobre, C.A. Amazon Savannization and Climate Change Are Projected to Increase Dry Season Length and Temperature Extremes over Brazil. *Sci Rep* **2024**, *14*, 5131.
93. Dos Reis, M.; de Alencastro Graça, P.M.L.; Yanai, A.M.; Ramos, C.J.P.; Fearnside, P.M. Forest Fires and Deforestation in the Central Amazon: Effects of Landscape and Climate on Spatial and Temporal Dynamics. *J Environ Manage* **2021**, *288*, 112310.
94. Yanai, A.M.; de Alencastro Graça, P.M.L.; Escada, M.I.S.; Ziccardi, L.G.; Fearnside, P.M. Deforestation Dynamics in Brazil's Amazonian Settlements: Effects of Land-Tenure Concentration. *J Environ Manage* **2020**, *268*, 110555.
95. Moretto, E.M.; Gomes, C.S.; Roquetti, D.R.; Jordão, C. de O. Histórico, Tendências e Perspectivas No Planejamento Espacial de Usinas Hidrelétricas Brasileiras: A Antiga e Atual Fronteira Amazônica. *Ambiente & Sociedade* **2012**, *15*, 141–164.
96. Pezzuti, J.C.B.; Zuanon, J.; Lopes, P.F.M.; Carneiro, C.C.; Sawakuchi, A.O.; Montovanelli, T.R.; Akama, A.; Ribas, C.C.; Juruna, D.; Fearnside, P.M. Brazil's Belo Monte License Renewal and the Need to Recognize the Immense Impacts of Dams in Amazonia. *Perspect Ecol Conserv* **2024**, *22*, 112–117.
97. Fearnside, P.M. Environmental and Social Impacts of Hydroelectric Dams in Brazilian Amazonia: Implications for the Aluminum Industry. *World Dev* **2016**, *77*, 48–65.
98. Schielein, J.; Frey, G.P.; Miranda, J.; de Souza, R.A.; Boerner, J.; Henderson, J. The Role of Accessibility for Land Use and Land Cover Change in the Brazilian Amazon. *Applied Geography* **2021**, *132*, 102419.
99. Nazareno, A.G.; Lovejoy, T.E. Giant Dam Threatens Brazilian Rainforest. *Nature* **2011**, *478*, 37.
100. Nobre, C.A.; Sampaio, G.; Salazar, L. Mudanças Climáticas e Amazônia. *Cienc Cult* **2007**, *59*, 22–27.
101. Sonter, L.J.; Herrera, D.; Barrett, D.J.; Galford, G.L.; Moran, C.J.; Soares-Filho, B.S. Mining Drives Extensive Deforestation in the Brazilian Amazon. *Nat Commun* **2017**, *8*, 1013.
102. Bombardi, L.M. *Agrotóxicos e Colonialismo Químico*; Editora Elefante, 2023; ISBN 6560080218.
103. Segata, J.; Grisotti, M.; Porto, R. COVID-19 in Brazil. *Vibrant (Brasilia)* 2022, *19*, e19900.
104. Bin, D. Dispossessions in Bolsonaro's Brazil during the Covid-19 Pandemic. *World Dev* **2024**, *177*, 106560.
105. Fonseca, E.M. da; Nattrass, N.; Lazaro, L.L.B.; Bastos, F.I. Political Discourse, Denialism and Leadership Failure in Brazil's Response to COVID-19. *Glob Public Health* **2021**, *16*, 1251–1266.
106. Giatti, L.L.; Ribeiro, R.A.; Nava, A.F.D.; Gutberlet, J. Emerging Complexities and Rising Omission: Contrasts among Socio-Ecological Contexts of Infectious Diseases, Research and Policy in Brazil. *Genet Mol Biol* **2021**, *44*, e20200229.
107. Escobar, H. 'A Hostile Environment.'' Brazilian Scientists Face Rising Attacks from Bolsonaro's Regime' Available online: https://www.science.org/content/article/hostile-environment-brazilian-scientists-face-rising-attacks-bolsonaro-s-regime (accessed on 28 June 2025).
108. Borges, L.F.R.; Bispo, F. Lei Do Marco Temporal e Violência Contra Povos Indígenas Na Amazônia. *Revista Científica do CPJM* **2024**, *3*, 366–392.
109. Portela, R.C.; Menezes, E.E. de; Silva, S.D. e Marco Temporal: O Projeto Político Do Agronegócio Ea Ameaça Aos Direitos Dos Povos Indígenas. *Serviço Social & Sociedade* **2024**, *147*, e-6628418.
110. West, T.A.P. Formal Designation of Brazilian Indigenous Lands Linked to Small but Consistent Reductions in Deforestation. *Ecological Economics* **2024**, *218*, 108093.
111. Lima, M.; do Vale, J.C.E.; de Medeiros Costa, G.; dos Santos, R.C.; Correia Filho, W.L.F.; Gois, G.; de Oliveira-Junior, J.F.; Teodoro, P.E.; Rossi, F.S.; da Silva Junior, C.A. The Forests in the Indigenous Lands in Brazil in Peril. *Land use policy* **2020**, *90*, 104258.
112. Zimbres, B.; Shimbo, J.; Lenti, F.; Brandão, A.; Souza, E.; Azevedo, T.; Alencar, A. Improving Estimations of GHG Emissions and Removals from Land Use Change and Forests in Brazil. *Environmental Research Letters* **2024**, *19*, 094024.
113. Blackman, A.; Veit, P. D Amazon Indigenous Communities Cut Forest Carbon Emissions. *Ecological Economics* **2018**, *153*, 56–67.

114. Kere, E.N.; Choumert, J.; Motel, P.C.; Combes, J.L.; Santoni, O.; Schwartz, S. Addressing Contextual and Location Biases in the Assessment of Protected Areas Effectiveness on Deforestation in the Brazilian Amazônia. *Ecological Economics* **2017**, *136*, 148–158.
115. CO *Agenda Legislativa Observatório Do Clima 2025*; Brasília, 2025;
116. Drüke, M.; Sakschewski, B.; von Bloh, W.; Billing, M.; Lucht, W.; Thonicke, K. Fire May Prevent Future Amazon Forest Recovery after Large-Scale Deforestation. *Commun Earth Environ* **2023**, *4*, 248.
117. Mullan, K.; Caviglia-Harris, J.L.; Sills, E.O. Sustainability of Agricultural Production Following Deforestation in the Tropics: Evidence on the Value of Newly-Deforested, Long-Deforested and Forested Land in the Brazilian Amazon. *Land use policy* **2021**, *108*, 105660, doi:https://doi.org/10.1016/j.landusepol.2021.105660.
118. Franklin, S.L.; Pindyck, R.S. Tropical Forests, Tipping Points, and the Social Cost of Deforestation. *Ecological Economics* **2018**, *153*, 161–171, doi:10.1016/j.ecolecon.2018.06.003.
119. Nobre, C.A.; Peña-Claros, M.; Arieira, J.; Brandão, D.O.; Riveros, F.V. Climate Change and Sustainability in Amazonia. In *Oxford Research Encyclopedia of Climate Science*; 2025.
120. Azevedo-Santos, V.M.; Fearnside, P.M.; Oliveira, C.S.; Padial, A.A.; Pelicice, F.M.; Lima, D.P.; Simberloff, D.; Lovejoy, T.E.; Magalhães, A.L.B.; Orsi, M.L.; et al. Removing the Abyss between Conservation Science and Policy Decisions in Brazil. *Biodivers Conserv* **2017**, *26*, 1745–1752, doi:10.1007/s10531-017-1316-x.
121. Moreira-Dantas, I.R.; Söder, M. Global Deforestation Revisited: The Role of Weak Institutions. *Land use policy* **2022**, *122*, 106383.
122. Macedo, G. Climate Security, the Amazon, and the Responsibility to Protect. *Brazilian Political Science Review* **2021**, *15*, e0007.
123. Lipscomb, M.; Prabakaran, N. Property Rights and Deforestation: Evidence from the Terra Legal Land Reform in the Brazilian Amazon. *World Dev* **2020**, *129*, 104854.
124. Merkus, E. The Economic Consequences of Environmental Enforcement: Evidence from an Anti-Deforestation Policy in Brazil. *World Dev* **2024**, *181*, 106646.
125. Nobre, I.; Nobre, C. The Amazonia Third Way Initiative: The Role of Technology to Unveil the Potential of a Novel Tropical Biodiversity-Based Economy. In; 2018 ISBN 978-1-78985-703-0.
126. Nobre, C.A. The Amazon Third Way Initiative/Amazonia 4.0. **2018**.
127. Dutra, D.J.; Silveira, M.V.F.; Mataveli, G.; Ferro, P.D.; da Silva Magalhães, D.; de Medeiros, T.P.; Anderson, L.O. Challenges for Reducing Carbon Emissions from Land-Use and Land Cover Change in Brazil. *Perspect Ecol Conserv* **2024**, *22*, 213–218.