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Cutting of dry forests in a semiarid region of northeastern Brazil

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Summary

Dry forests are one of the most threatened ecosystems in the world, and they are poorly protected. The semiarid region of northeastern Brazil is the largest area in the New World with a predominance of dry forests, although it has been estimated that half of Brazil's original semiarid vegetation has already been removed. This study assesses the extent of changes in areas covered by native dry forests (*Caatinga*) over a period of 46 years (1973-2019) in the southern portion of the semiarid region in Brazil's State of Bahia. The study area encompasses 18 municipalities (counties) in a total area 2,344,733 ha. To map changes in vegetation cover, Landsat satellite images were used for the years 1973, 1987, 2001 and 2019. The area with native vegetation was reduced by 614,100 ha between 1973 and 2019. The area with vegetation declined in all municipalities, however, the intensity of changes in land use varied among the analyzed periods, with 77.1% of the reduction in vegetation cover occurring between 1973 and 1987. In the 1990s the intensity of cutting of native vegetation decreased, mainly due to a decrease in the area planted to cotton, while natural regeneration increased. Cutting native vegetation resumed in the 2000s while regeneration declined. In 2019 the remaining vegetation was almost completely restricted to hills or mountains and was in fragments composed of a mosaic of vegetation in different stages of regeneration. Areas that still have native vegetation must be preserved, including those that are regenerating from past clearing.

Keywords: semiarid vegetation, deforestation, dry lands, seasonal dry forests, environmental services, Brazil.

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1 - Introduction

Forests in the tropical regions of the world are threatened, with global forest area having declined substantially in recent decades, losing 314 million hectares between 2001 and 2015 (Curtis et al. 2018; FAO 2018; Hansen et al. 2013). Deforestation remains especially high in rainforests or humid forests in the tropics, but in tropical dry forests it has also been alarming (Hansen et al. 2013). The global extent of drylands has been estimated at 6.1 billion hectares (41% of the Earth's land surface), with 1.1 billion hectares occupied by dry forests, which is equivalent to 27% of the areas occupied by forests in the world (Bastin et al. 2017; FAO 2019). Drylands are regions where the ratio between annual precipitation and average annual potential evapotranspiration (the aridity index) is not greater than 0.65 (FAO 2019; Sörensen 2007). Vegetation in drylands is considered to be "dry forest" if it occupies an area equal to or greater than 0.5 ha with trees taller than 5 m (or trees capable of reaching this potential) and a canopy cover greater than 10% (FAO 2012).

South American drylands occupy 545 million hectares (9% of global drylands) according to FAO's global drylands assessment (FAO 2019) and harbor 54.2% of the world's remaining dry forests (Miles et al. 2006). South American dry forests have higher endemism and average canopy cover than the dry forests on other continents (Dryflor et al. 2016; FAO 2019). South American seasonally dry tropical forests are severely threatened, with less than 10% of their original extent remaining in many countries (Dryflor et al. 2016; Hansen et al. 2013; Miles et al. 2006).

The semiarid region of northeastern Brazil is the largest area in the New World with a predominance of dry forests (~850,000 km^2) (Brazil IBGE 2019; Fernandes and Queiroz 2018). This region has a distinct floristic group of neotropical dry forests known as "*caatinga*" (Dryflor et al. 2016). The *caatinga* generally occurs on extensive flat surfaces with altitudes ranging from 300 to 500 m, interspersed with plateaus that can reach 1000 m. The plains are normally occupied by dry forests and deciduous shrub vegetation, while the plateaus are occupied by different types of vegetation, such as humid forests, *cerrado* (central Brazilian savanna) and "*rupestre*" vegetation characteristic of rocky areas (Tabarelli et al. 2018). During the rainy season the *caatinga* is exuberant and the foliage of the trees is abundant, while in the dry season practically all the leaves fall, leaving the dry branches and the vegetation appearing to be dead (Fernandes and Queiroz 2018). Despite the low rainfall, the rate of plant richness is high. Many species and genera are restricted to these dry forests. Many of the plant species are locally abundant or dominant, although geographically restricted (Dryflor et al. 2016; Fernandes and Queiroz 2018). Unlike many of the world's dry forests, the *caatinga* is not characterized by a few oligarchic species predominating on a large scale. Among 12 floristic groups of dry forests identified in the Neotropical region, 23 to 73% of the species found are exclusive to these groups, which indicates that the lack of protection of dry forests could result in the loss of unique species (Dryflor et al. 2016; Fernandes and Queiroz 2018).

Although shrub vegetation is predominant, there are several vegetation types occupying extensive areas in the *caatinga* (Brazil IBGE 2002; Velloso et al. 2002; Veloso et al. 1991). For example, within the limits of Brazil's "*Caatinga* Biome" (an officially defined geographical area in which *caatinga* is the predominant, but not the only, original vegetation type), seasonal dry deciduous forests occur, which, although poorly protected and poorly researched, are among the most threatened tropical forests in the world (Espírito-Santo et al. 2006; Vieira 2006). Dry deciduous forests are exuberant formations whose canopy height can reach 40 m, being rich in plant and animal diversity (Murphy and Lugo 1986). These precious forests are the habitat of various threatened plant species, among them species with commercially valuable wood, such as aroeira (*Myracrodruon urundeuva* Engl.), pau-d'arco (*Handroanthus impetiginosus* (Mart. ex DC.) Mattos), and peroba (*Aspidosperma polyneuron*). The areas of dry deciduous forests have been devastated in the *caatinga*, with the remaining areas being scarce and generally restricted to fragments (Vieira 2006).

Despite the limitations associated with low rainfall in dry forests, the main threat is not the scarcity of rainfall, but rather deforestation and degradation of native vegetation (Curtis et al. 2018).

In 2008, 1921 km² of native vegetation was cleared in the *Caatinga* Biome (Brazil IBAMA 2011). Between 2002 and 2008, the average deforestation per year was 2763 km², reaching a total of 16,576 km² in just 6 years (Brazil IBAMA 2011). By 2009, 45% of the original vegetation cover of the *Caatinga* Biome had already been cut and replaced by other forms of cover and land use (Brazil IBAMA 2011). Recent studies have estimated that half the original *caatinga* vegetation has already been removed (Antongiovanni et al. 2020).

Despite the alarming rate of degradation and the fact that little intact *caatinga* vegetation remains, the *Caatinga* Biome is one of the least monitored and protected in Brazil. Until early 2020, only 8.8% of the *Caatinga* Biome was protected by "conservation units" ("*unidades de conservação*" or "UCs"). In Brazil, UCs are officially grouped into two categories: "full protection" and "sustainable use." Only 2.2% of the *Caatinga* Biome was in "integral-protection" UCs (Boff 2018; Dryflor et al. 2016; Garda et al. 2018). Most of the area in UCs for sustainable use is in "environmental protection areas" ("*áreas de proteção ambiental,*" or "APAs"), which is the most permissive category of conservation unit (Brazil CNUC 2020; Fonseca et al. 2018).

In the *caatinga*, natural vegetation is normally removed for agricultural crops, pasture, firewood extraction, commercial exploitation of hardwoods or for the manufacture of charcoal (Curtis et al. 2018; Ribeiro et al. 2015). These changes in land cover promote different levels of impact, with desertification being the final consequence. Desertification already threatens one-third of the Northeast Region of Brazil, with 200,000 km² already classified as being at serious or very serious risk of desertification (Sá and Angelotte 2009; Vieira 2015). The frequency and magnitude of these impacts have made the *caatinga* one of the most threatened semiarid ecosystems in the world. There is a lack of environmental inspection and of actions to encourage sustainable forms of land use and the effective implementation of priority areas for conservation (Fonseca et al. 2018; Ribeiro et al. 2015).

In the southern part of the semiarid region of Bahia, the environmental impacts have been especially intense in the last 50 years, when there were high rates of annual deforestation in areas originally covered by typical *caatinga* vegetation and by seasonal dry deciduous forests. Although this is an ecological transition zone rich in biodiversity (Fonseca et al. 2018) and in endemic species (*e.g.,* Costa and Amorim 2011), it continues to suffer multiple anthropogenic environmental impacts. In addition, the dynamics of land use change have been poorly estimated through the time in this important area. This information is essential to identify hotspot areas for conserving what remains of the caatinga.

The objective of this study was to assess the spatial and temporal dynamics of native vegetation change over a 46-year period (1973-2019) and to evaluate the influence of anthropogenic and biophysical variables on the spatial distribution of land-use and land-cover change during this period. The study area encompasses the southern part of the semiarid region of the State of Bahia in Brazil's Northeast Region with a total area of 23,447 km^2 (roughly equivalent to two-thirds of Belgium).

2 - Materials and Methods

2.1. Characterization of the study area

The Guanambi microregion is located in the southern part of the semiarid region of the State of Bahia, in the middle São Francisco River basin in northeast Brazil, occupying 2,344,733 ha (Figure 1). In 2010, 371,379 people lived in the 18 municipalities in the Guanambi microregion, and 53.1% of the population was in rural areas (Brazil IBGE 1990, 2010). "Municipalities" in Brazil are political units roughly equivalent to counties, and "microregions" are groups of municipalities used for census and other official data by the Brazilian Institute of Geography and Statistics (IBGE). In this microregion 459.7 km² is delimited as conservation units: the Serra dos Montes Altos Wildlife Refuge (274.9 km²) and the Serra dos Montes Altos State Park (184.8 km²). There are also four

Private Natural Heritage Reserves (RPPNs), three located in the municipality of Malhada and one in the municipality of Palmas de Monte Alto. However, there are no official estimates of the extent of these RPPNs in the National Register of Conservation Units (Brazil CNUC 2020).

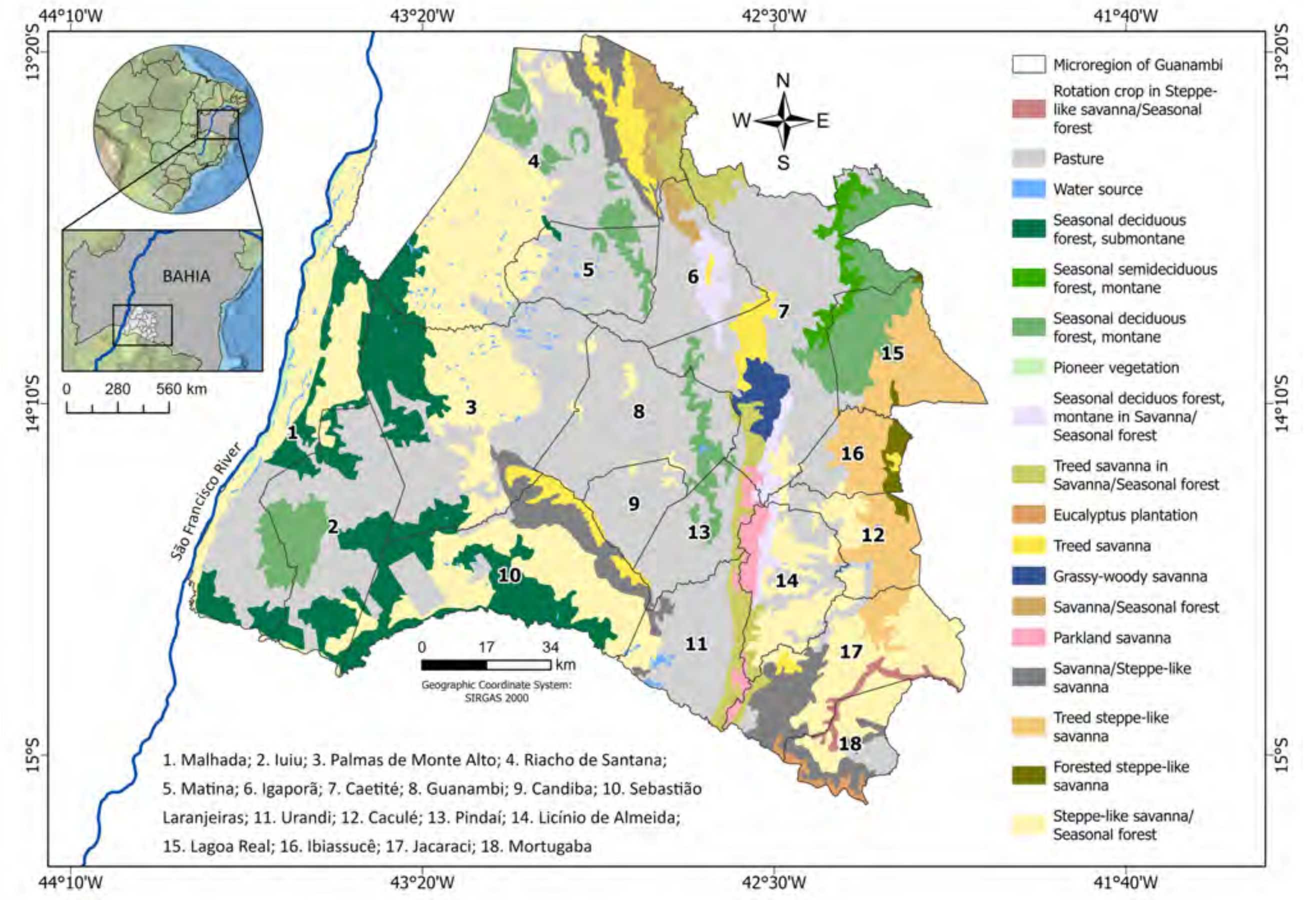

Figure 1. Location of the study area (with vegetation types and names of municipalities), in the southern portion of the semiarid region of Bahia state, in northeastern Brazil.

The study area is a zone of ecological tension (ecotone) where different types of vegetation occur. There is steppe-like savanna (the nomenclature adopted for *caatinga* in the Brazilian Vegetation Classification), fragments of ombrophilous savanna, and seasonal dry forests in areas where soils are more fertile and water supply is relatively greater (Brazil IBGE 2012; Mooney et al. 1995; Veloso et al. 1991). Several types of ombrophilous savannas occur associated with elevated areas with poorer soils. Steppe-like savannas are common in depressions, and currently consist of a mosaic of secondary vegetation in different stages of regeneration (Brazil IBGE 2004). Diffuse patches of montane or submontane deciduous forest originally occurred over vast areas, but these forests are now scarce due to cutting to extract wood and establish pastures. Additional information about soils, climate and precipitation characteristics are available in the Supplementary Material.

2.2. Multi-temporal mapping of areas covered by vegetation

Selection of images for mapping changes in land cover between 1973-2019 was based on the combination of two criteria: (i) less cloud cover, which usually occurs in the driest months of the year (August to October), and (ii) the oldest possible images in order to allow assessing changes in vegetation cover over the widest possible time interval. The oldest images obtained were from 1973, which is why this year was set as the starting time for the mapping. Cloud-free images in intermediate periods of 14 to 18 years (images from 1987 and 2001) were also chosen to assess the spatio-temporal dynamics of changes in vegetation cover. The areas with vegetation in 1973, 1987, 2001 and 2019 were mapped using images from the Landsat 1, 5 and 8 satellites (Table S1). The images were obtained from the website https://www.usgs.gov/.

Portions of the Guanambi microregion covered with vegetation were diagnosed in satellite images using supervised classification by the decision-tree method in ENVI 5.5 (2018) software. With this classifier it is possible to use several stages in a series of binary decisions, dividing the set of pixels into subsets for each determination. Various types of cartographic data can be used to refine the classification (Maeda et al. 2011). The algorithm used data from the spectral channels of the Landsat 1, 5 and 8 satellites to determine the Normalized Difference Vegetation Index (NDVI) and identify regionalized geomorphological features. The study area was regionalized based on geomorphological criteria, aiming to reduce the degree of confusion between the targets. Thus, the area of the São Franciscana Depression was separated from the higher-elevation areas in the Serra do Espinhaço mountain range. A scale of 1:160,000 was adopted for the classification for the year 1973, and 1:60,000 was adopted for other years. After the classification, polygons were assigned to each area mapped with vegetation. The minimum unit of each polygon was 2 ha. The post-processing and cross-referencing between cartographic bases were carried out through the refinement of the classification through superposition, photointerpretation and adjustment of the polygons.

The classification derived from the orbital products was evaluated in terms of overall accuracy and by means of the Kappa coefficient, which uses error matrices for statistical measures of robustness. The main characteristic of overall accuracy is the use of the principal diagonal of the set of pixels of the selected classification in a comparison with the most reliable samples. The Kappa coefficient relates the scene's confusion matrix to the reference points, including points off the principal diagonal. This indicator is a nominal-scale coefficient with values ranging from 0 to 1 (Congalton 1991; Stehman 1992).

In the Guanambi microregion, 74 samples were selected, 30 of which were collected in the field and 44 acquired from high-resolution images for the years 2018 and 2019 (Google Earth platform). Overall accuracy was 81.1% and the Kappa coefficient was 0.626, which are values that indicate a very good classification of the categories (Landis and Koch 1977). In addition to the samples mentioned, a greater number of field visits was carried out with the aim of comparing observations from images with reality in the landscape. Field visits took place in April and August 2018, April, May, June, August and September 2019, and March 2020 in the municipalities of Candiba, Guanambi, Igaporã, Matina, Palmas de Monte Alto, Pindaí, Sebastião Laranjeiras, Riacho de Santana and Caetité. In each of the locations visited, photographic records and geographical coordinates (GPS points) were obtained. These visits contributed to a better understanding of the dynamics of land-cover change in the microregion that was the object of this study.

2.3. Multi-temporal analysis of changes in vegetation cover

The area without vegetation cover (*i.e.,* “other types of land use”) was estimated for 1973 (the initial year). In each of the years evaluated, the areas covered with vegetation were identified, and mapped, and their areas were estimated together with the changes in areal extent between 1973 and 2019 (interval of 46 years), between 1973 and 1987 (14 years), between 1987 and 2001 (14 years old) and between 2001 and 2019 (18 years). In each of the intervals we estimated (i) the extent of vegetation cutting (vegetation → other land uses), (ii) the extent of vegetation regeneration (other types of land use → vegetation), and (iii) the spatial changes between cutting and regeneration. The changes in the areas with vegetation that occurred in each municipality were also quantified in these intervals, as well as the fragmentation of the vegetation. In this study the term “vegetation” refers to the vegetation that naturally occurs in the microregion (Figure 1), common in the Brazilian semi-arid region, according to the Brazilian classification (Veloso et al. 1991). Commercial plantings of exotic forest species were observed only in the extreme south of the microregion, in the municipality of

Mortugaba (Figure 1). Other exotic forest species may be present around rural residences, in backyards with a few trees (*e.g., Leucaena* spp., *Prosopis juliflora* (Sw.) DC.). The "other types of land use" class includes areas without vegetation since 1973 or areas under other forms of land use, such as rocky outcrops, urban sites, and waterbodies.

Here, reduction in the areal extent of vegetation is not synonymous with deforestation. Deforestation involves the transition – usually abrupt – from an area covered with trees to a scenario without trees (*i.e.,* clear-cutting), without subsequent regrowth (Curtis et al. 2018). The estimates in our study are not restricted to the sum of the areas where there was deforestation, but rather include the result of the subtraction between the areas where the vegetation was removed and the abandoned areas that were regenerated. For example, areas that regenerated after deforestation over a given interval and that, at the end of a given year under analysis, were covered by vegetation, were mapped and considered as "remaining vegetation." Thus, the changes in vegetation cover estimated over the 46-year period refer to the differences between the extent of areas with remaining native vegetation in 2019 and the extent with vegetation in 1973.

2.4. Classification of vegetation in areas with remaining cover

Vegetation types (Figure 1) in areas mapped with remaining or suppressed vegetation were classified using a 1:250,000 scale vegetation map developed from the RadamBrasil Project surveys (Brazil Projeto RadamBrasil 1972-1983). Identification of vegetation types in each polygon mapped with vegetation was based on the intersection between the classified maps for the years analyzed with the vegetation map. This procedure also made it possible to identify the vegetation originally existing in areas where vegetation was cut. The nomenclature of vegetation types follows the classification of the Brazilian Institute of Geography and Statistics (IBGE), as specified in the Technical Manual of Brazilian Vegetation (Brazil IBGE 2012).

2.5. Relationship between changes in land cover and anthropogenic and biophysical variables

To understand how the dynamics of land-use and cover change is related to anthropogenic and biophysical aspects of the study area, anthropogenic variables (distances to other uses and distance to roads) and biophysical variables (slope, soil and vegetation) were analyzed. These variables were related to the maps resulting from the supervised classification described above (Section 2.2). The areas whose use or land cover is different from forest were denominated "other uses." Three time-intervals were analyzed: (i) 1973-1987; (ii) 1987-2001; (iii) 2001-2019. For this analysis, the weights-of-evidence method available in Dinamica-EGO software (https://csr.ufmg.br/dinamica/) was used (Soares-Filho et al. 2009). The weights-of-evidence method is a Bayesian probability method developed to predict the occurrence of binary events (Bonham-Carter et al. 1989). In our case, this method makes it possible to evaluate the relationship between deforestation (*i.e.,* "other uses") and biophysical and anthropogenic variables through the weights-of-evidence contrast values. This analysis determines the probability of an event occurring based on evidence (Bonham-Carter et al. 1989). To calculate the weights-of-evidence contrast values, a transition from the class "forest" to the class "other uses" was determined. Positive values of weights indicate a high chance of the event occurring (*i.e.,* change of forest to other uses). Negative values indicate that certain distance ranges or categories of the analyzed variable inhibit the occurrence of the event. Values close to zero indicate that a variable or distance range has no effect on the occurrence of the event (Soares-Filho et al. 2009).

The variable "distance to roads" considered federal and state highways (Brazil DNIT 2022). For each period analyzed, the map of existing roads was updated through visual interpretation of satellite images because we could not find the exact year of construction for some of the highways. In the study area we found a total of 14 state highways and two federal highways (Figure S1). For the variable "distance to other uses" we used the classified maps of vegetation and of other uses elaborated in the previous stages. To generate the distances, a “functor” (a tool in Dinamica-EGO software) called “Calc Distance Map” was used that calculates the Euclidean distance of the variable of interest. The altitude and slope maps were derived from SRTM (Shuttle Radar Topography Mission) data. Vegetation and soil maps were obtained from the mapping and classification carried out by IBGE. Vegetation types were grouped into three main categories: (i) forest formations (ii) contact zone between savanna and forest and (iii) other types of vegetation.

The variable maps were all resized based on the Landsat image for 1973, where each cell (pixel) represented 80 × 80 m. The assumption for calculating the weights-of-evidence contrast is that the variables are spatially independent (Agterberg and Cheng 2002). To test this, we used the Cramer and the Point Information Uncertainty tests (Soares-Filho et al. 2009). Test values lower than 0.5 indicate spatial independence between the variables, a threshold that has been used in other studies (*e.g.,* Almeida et al. 2005; Reis et al. 2021; Yanai et al. 2012). All analyzed variables had test values lower than 0.5 in both tests, indicating spatial independence between them. It was therefore not necessary to exclude any variable in any of the intervals analyzed.

3. Results

3.1. Dynamics of change in vegetation cover

The total extent of areas with vegetation was reduced by 614,100 ha between 1973 and 2019. Estimates do not distinguish possible primary formations from those in secondary stages. Consequently, in addition to the difference in the extent of areas with vegetation, and eventual spatial differences, the formations mapped in 2019 differ from the vegetation that existed in 1973, either because they consist of old plant formations with different levels of degradation, or of secondary formations in different stages of regeneration. The areas that were with vegetation in 1973 but without vegetation in 2019 are presented in Figure 2.

Although the changes were characterized by a generalized reduction in vegetation cover in the microregion, the intensity at which these changes occurred varied over the years evaluated. Until 1973, deforestation had predominated in the central portion of the microregion, and since then it has been consolidated in this area (Figure 2). In 1973 1.6 million km² was estimated to be covered by vegetation (Table 1). However, before the end of the following decade (1987) the landscape had already been drastically altered and vegetation cover reduced to 1.12 million km². This reduction represents 77.1% of the total estimated during the 46 years analyzed. The rapid rate of cutting vegetation during the 1980s decreased during the following decade, accompanied by an increase in regeneration, which surpassed deforestation in approximately 70% of the municipalities, resulting in 35,700 ha more vegetation in 2001 when compared to 1987. The reduction of areas with vegetation resumed in the 2000s, while the expansion of regeneration slowed during the same period. The cutting and regeneration of vegetation are shown in Figure 3 for each municipality and time interval. The process of vegetation reduction continued at the end of the period analyzed in this study, albeit at a slower pace (Figure 3). The balance in 2019 is a significant reduction in the area with vegetation cover in the microregion (Figure 2).

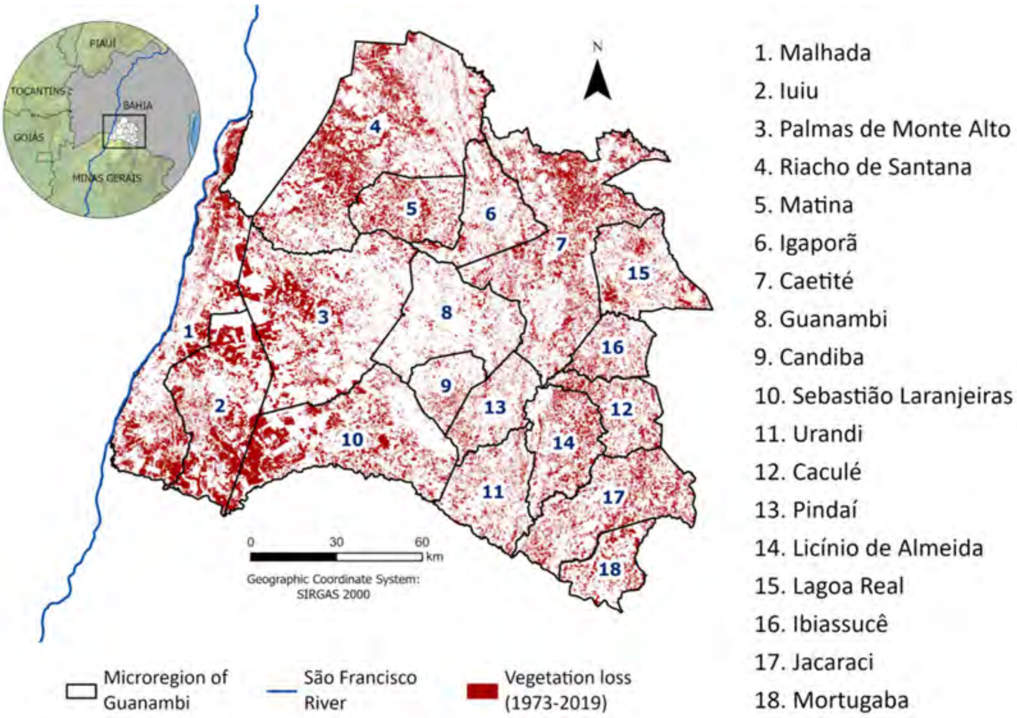

Figure 2. Vegetation loss between 1973 and 2019 in 18 municipalities in the semiarid region of Bahia state, Brazil. Areas in red were with vegetation in 1973 but without vegetation in 2019. Blank areas refer to (i) areas with vegetation remaining in 2019 that were never fully deforested after 1973 but that regenerated later; (ii) areas without vegetation since 1973, or (iii) areas under other forms of land use, rocky outcrops, urban sites, waterbodies, etc.

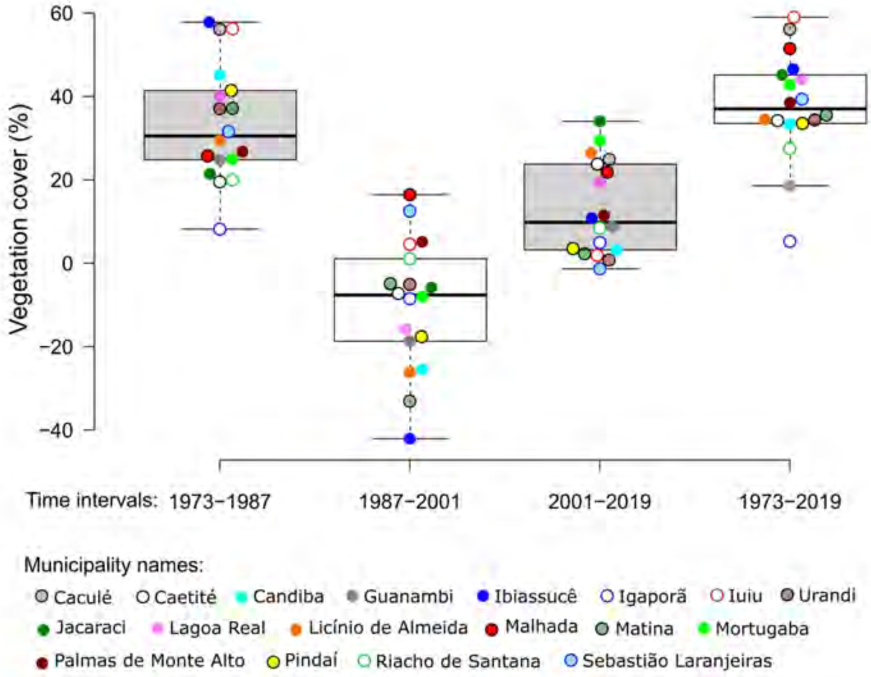

Figure 3. Percentage of vegetation loss (positive values) or regeneration (negative values) in different time intervals by municipality (colored circles) in the southern portion of the semiarid region of Bahia state, Brazil.

Table 1. Vegetation dynamics by municipality in the Guanambi microregion between 1979 and 2019.

Municipality	Total area (ha)*	Remaining vegetation in 2019 (ha)	Remaining vegetation in 2019 (%)	Vegetation loss 1973-2019 (ha)	Vegetation loss 1973-2019 (%)
Caculé	61,098.4	23,339.9	38.2	29,848.4	56.1
Caetité	265,153.7	142,532.7	53.8	74,041.4	34.2
Candiba	43,364.2	10,589.4	24.4	5,306.5	33.4
Guanambi	127,236.4	25,538.8	20.1	5,824.2	18.6
Ibiassucê	48,327.4	21,583.0	44.7	18,772.9	46.5
Igaporã	83,658.2	41,803.0	50.0	2,312.1	5.2
Iuiu	152,234.4	39,393.8	25.9	56,674.8	59.0
Jacaraci	133,241.8	64,277.3	48.2	52,923.3	45.2
Lagoa Real	91,222.3	41,870.7	45.9	33,038.2	44.1
Licínio de Almeida	85,662.3	50,533.8	59.0	26,607.0	34.5
Malhada	197,171.4	59,742.6	30.3	63,363.5	51.5
Matina	77,328.1	26,497.3	34.3	14,606.9	35.5
Mortugaba	52,821.6	25,943.9	49.1	19,399.4	42.8
Palmas de Monte Alto	256,281.4	86,566.9	33.8	54,211.1	38.5
Pindaí	62,847.6	21,880.7	34.8	11,041.6	33.5
Riacho de Santana	318,391.7	168,184.3	52.8	63,806.6	27.5
Sebastião Laranjeiras	198,452.1	96,776.7	48.8	62,731.2	39.3
Urandi	90,240.4	37,524.0	41.6	19,643.8	34.4
Total	2,344,733.3	984,578.6		614,152.9	

In terms of spatial distribution, deforestation advanced from 1973 onwards radially from the central portion towards the edges of the microregion, but it advanced more intensely to the west, especially in the southwest quadrant (Figure 4). The direction of the expansion of deforestation was driven by access via Highway BR-030 and by the attractiveness of the low plains with fertile soils, both in the southwestern and northwestern portions of the microregion (Figure 4).

The municipalities of Iuiu, Caculé and Malhada had the largest percentage reductions in vegetation cover in 2019 as compared to the extent of vegetation in 1973 (Figure 3). The smallest percentage losses occurred in the municipalities of Igaporã, Guanambi and Riacho de Santana. In the municipality of Guanambi, located in the geographic center of the microregion, there was less loss and less area with remaining vegetation in the 1973-2019 interval because there had already been a significant reduction in vegetation cover before 1973 (Figures 2 and 4).

There was a high correlation between the extent of the cumulative deforestation that occurred between 1973 to 2019 in a municipality with the territorial extent of the municipality (r^2 adj. = 0.67, $p < 0.0001$, Intercept: 30906.03, Coefficient: -2.9120; Figure 5). In accordance with this pattern, the six largest of the 18 municipalities in the microregion occupy 59.2% of the territory and accounted for 61% of the cumulative deforestation. In each of these municipalities, the reduction in the area covered with vegetation exceeded 54,000 ha over the 46-year period (Table 1), ranging from 54,200 ha (Palmas de Monte Alto) to 74,000 ha (Caetité).

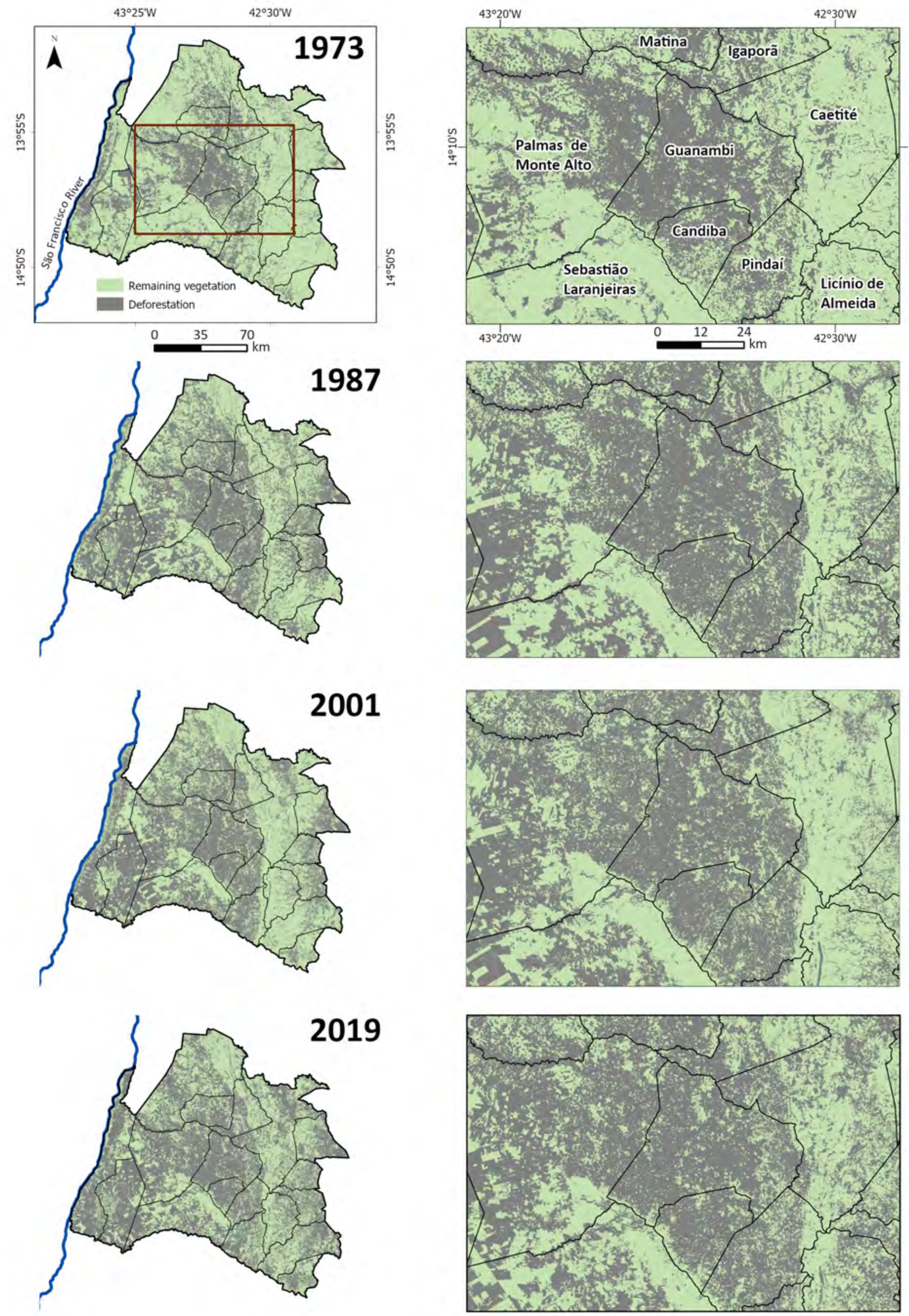

Figure 4. Change in vegetation cover between 1973 and 2019 focusing on the southwestern portion of the Guanambi microregion in Bahia state, Brazil.

The municipalities with the greatest absolute extent of remaining vegetation mapped in 2019 were Riacho de Santana, Caetité and Sebastião Laranjeiras. The municipalities of Licínio de Almeida, Caetité and Riacho de Santana were those with the highest percentages of remaining vegetation (> 50% of the territory) (Figure 4, Table 1). The municipalities with the lowest percentages of their total areas with remaining vegetation were Guanambi, Candiba and Iuiu (Table 1). The extent of remaining vegetation per municipality is naturally related to the territorial extent of the municipality, but it is also related to the occurrence in the territory of mountains or other formations that are unattractive for cutting vegetation.

In all municipalities, the remaining vegetation normally consists of a mosaic of secondary vegetation in different stages of succession, with rare patches of the remaining vegetation having characteristics typical of primary vegetation. Larger continuous areas with remaining vegetation are scarce in the Sertaneja depression areas of the microregion, the remaining vegetation being restricted to diffuse fragments. Extensive continuous areas covered by vegetation are restricted to mountains and hills. Municipalities with ≥ 50% of their territory with remaining vegetation in 2019 had at least part of their territory located in higher-elevation areas (Table 1).

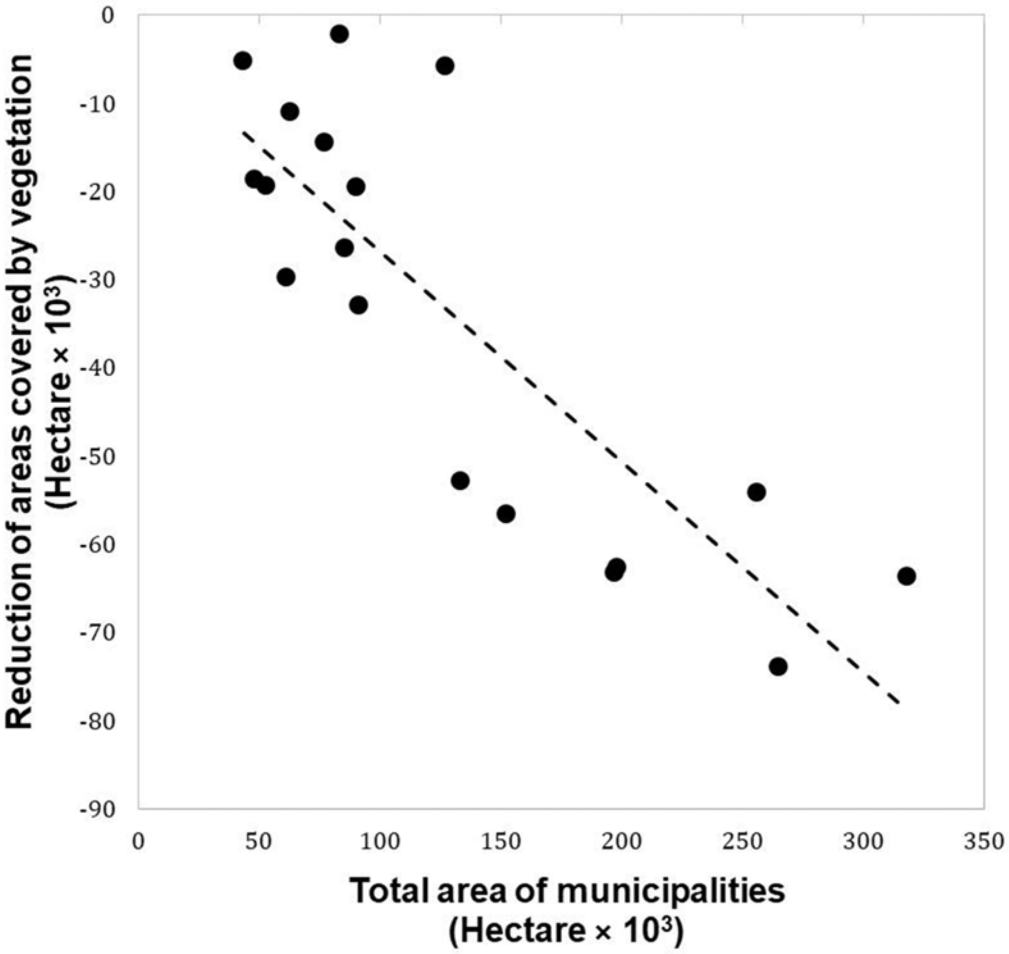

Figure 5. Relation between the territorial extent of the municipalities in the Guanambi microregion and the cumulative reduction in vegetation cover between 1973 and 2019.

3.2 Relationships between deforestation and anthropogenic and biophysical variables

The analysis of the weights-of-evidence from 1973 to 1987 showed that cutting vegetation occurred mainly in areas < 240 m from those already deforested for other uses (Figure 6). In addition, deforestation generally occurred within ~7 km of the main roads. A small increase in the weights-of-evidence values occurred far from the main roads, which could be associated with other factors related to the land-use change dynamics in the region. Deforestation occurred more in areas with lower slope values and less in areas with steeper terrain (Figure 6).

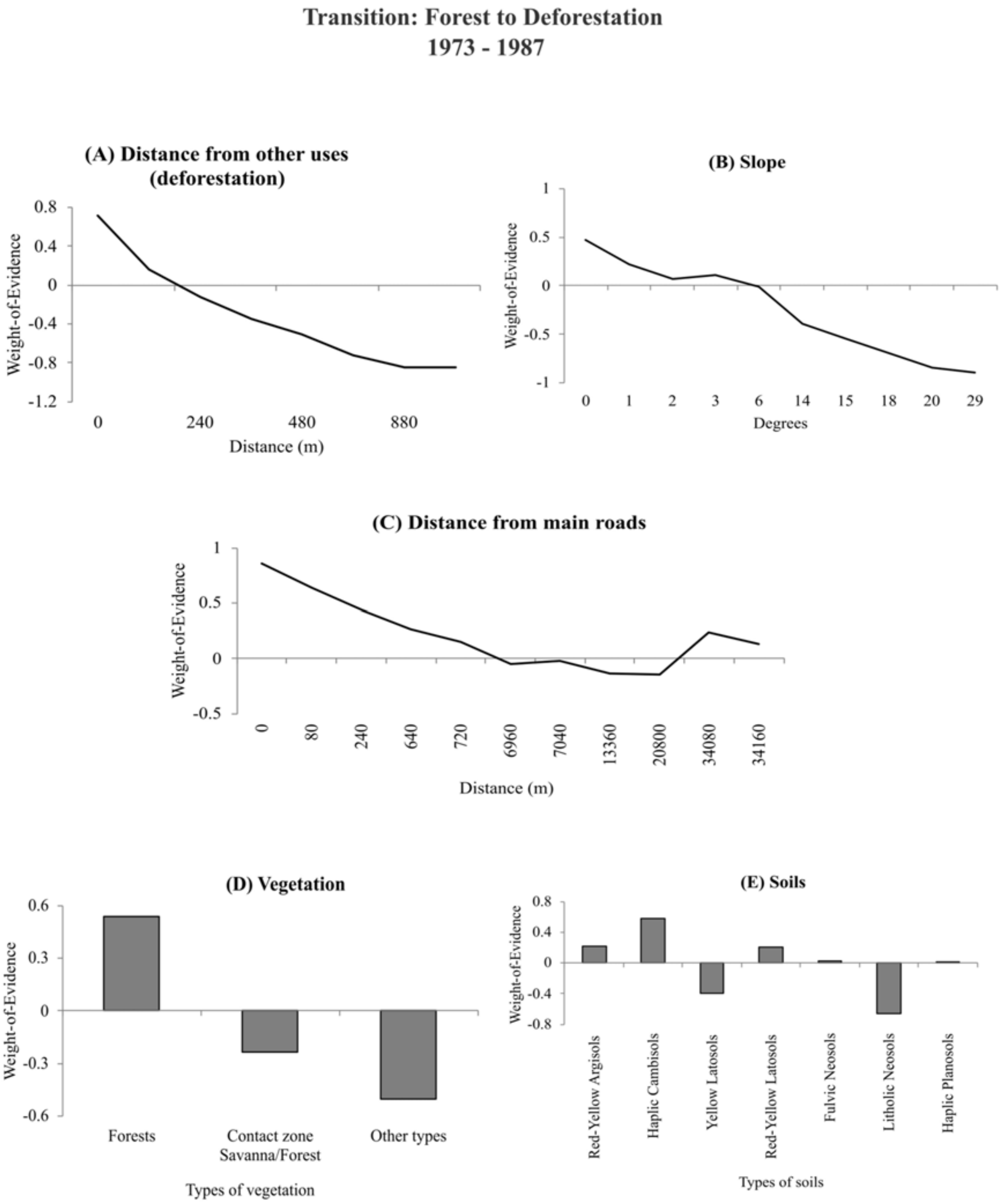

Figure 6. Values of the weights-of-evidence contrasts for the biophysical and anthropogenic variables in the period from 1973 to 1987. (A) "Other uses" refers to deforestation; (C) "Main roads" refers to a federal and state highways; (D) Forest formations represent seasonal deciduous and semideciduous forests. "Contact zone" is between savanna and seasonal forest or between steppe-like savanna and seasonal forest. "Other types of vegetation" refers to classes such as different types of savanna (*e.g.,* treed savanna, steppe-like savanna, and parkland savanna), pioneer formations, etc.

Soil types on which there was the highest occurrence of deforestation, resulting in positive values of weights-of-evidence, were: red-yellow argisol, haplic cambisol and red-yellow latosol (Figure 6). Based on both anthropogenic and biophysical variables, a probability map for 1973 indicated areas with high chance of deforestation. These areas were consistent with the changes observed from 1973 to 1987 (Figure S2). Thus, the variables used were sufficient to capture the pattern of land-use change. For the 1973-1987 period, areas with forests were more susceptible to being cleared as compared to areas in contact zones and areas with other types of vegetation (Figure 6).

From 1987 to 2001, the pattern of weights-of-evidence for the variables "distance from other uses" and "slope" was similar to that observed in the first period (1973-1987), where areas close to deforestation and with lower slope values were more attractive for deforestation. In contrast, we observed a distinct pattern for the variable "distance from other uses" and in types of vegetation where, in this period, areas in the contact zone between savanna and forest were more attractive to deforestation in comparison with areas in forests. In the case of the main roads, deforestation generally occurred in a more distant range (> 11 km to 55 km from the road) than that observed in the first interval. In this period, deforestation was concentrated in the eastern portion of the region. Although an increment of main roads also occurred in this portion of the region, deforestation was not concentrated mainly in the area along roads, indicating that the expansion of human occupation and economic activities occurred with a more diffuse pattern in the eastern part of the Guanambi microregion (Figure S3). Areas with the red-yellow latosol, fluvic neosol and haplic planosol soil types were more attractive for deforestation as compared to the other soil types (Figure S3).

In the most recent interval (2001-2019), the weights-of-evidence indicated that the vegetation existing in 2001 was more susceptible to being deforested in areas close to other uses (*i.e*, previously cleared areas), in areas close to federal and state highways and in areas with lower values for slope (Figure S4). Deforestation occurred mainly in the contact zone between savanna and forest and on the haplic cambisol, yellow latosol, fluvic neosol and haplic planosol soil types (Figure S4).

4. Discussion

4.1. Dynamics of change in the native vegetation cover

Tropical dry forest is one of the most threatened terrestrial ecosystems on the planet, with a rapid rate of vegetation conversion to areas of agricultural use (Hansen et al. 2013; Vieira et al. 2015). The present study contributes to a better understanding of the changes in vegetation cover in the southern part of the most extensive semiarid region in South America. As in other threatened dry forests in the world, the vegetation cutting investigated in this study was related to agriculture, livestock and extractive activities such as harvesting wood for charcoal (Curtis et al. 2018).

From 1973 to 1987, the intensity of degradation or the clear-cutting of the vegetation was mainly driven by the demand for agricultural land. In these years, the reduction of vegetation cover coincided closely with the expansion of agricultural crops in the microregion, especially cotton (Brazil IBGE 1975-1995; dos Santos 2011). It is estimated that the annual planting of cotton reached 180,000 ha in the Iuiu Valley alone (Beltrão 2003). Land use for livestock and for planting other crops, such as corn and beans, occurred at a lower intensity. The planted area and cotton production in the municipalities of the Guanambi microregion (which includes the Iuiu Valley) expanded rapidly from the late 1970s onwards, remaining high until the late 1980s. IBGE's agricultural census recorded a cotton production of 22,800 tons in the State of Bahia in 1975. In 1980 production was estimated at 26,700 tons, reaching a peak of 143,400 tons in 1985. Production in Bahia fell to only 43,700 tons in 1995 (Brazil IBGE 1975-1995). In the municipalities of the microregion, estimates from the Brazilian Agricultural Census indicated that 24,400 ha were used for cotton seed production in 1975, 28,200 ha in 1980 and 107,100 ha 1985 (Brazil IBGE 1979, 1983, 1991).

This dynamic reflects the pattern of expansion and decline of cotton, the main temporary crop grown in the microregion in that period (dos Santos 2011). Cotton cultivation in this microregion reached 300,000 ha but was reduced to zero at the end of the 1990s (Gonçalves 2007). This was due to attack by weevils in the family Curculionidae, inadequate soil management and the surge in imports that occurred in Brazil in that period (Gonçalves 2007; Morello et al. 2009).

Deforestation in the 1970s and 1980s spread mainly in the western part of the microregion (both in the northwestern and southwestern portions) (Figure 4). This process continued towards the São Franciscan plain in areas with flat relief, while, in the opposite direction (to the east) the relief is dominated by hills and mountains (Figure 4). In addition to the flat relief, in the western portion of the microregion there was denser vegetation on more fertile soils. Flat topography is needed for mechanized crops such as cotton. The process of replacing vegetation with cotton plantations was especially intense in the Iuiu Valley, which is famous for having soils with high natural fertility (Morello et al. 2009). This portion of Bahia was one of the main cotton-producing regions in Brazil due to its high-fertility soils, flat relief, and sufficient rainfall and solar radiation, which is crucial for better cotton fiber quality (Gonçalves 2007). It is estimated that the Iuiu Valley, together with other parts of the Guanambi microregion, accounted for 19% of the cotton produced in Brazil (Beltrão 2003). We showed the rapid removal of vegetation in the municipality of Iuiu in the historical period (Table 1, Figure 4). During the 1980s, the Iuiu valley (which includes parts of municipalities neighboring the municipality of Iuiu) was the main cotton producing region in the state of Bahia (dos Santos 2011; Gonçalves 2007).

With the decrease in cotton cultivation between 1987 and 2001, crops such as beans, corn and sorghum, as well as livestock, began to occupy areas previously planted with cotton (dos Santos 2011). Simultaneously, some of the extensive areas previously used for cotton were abandoned or lay dormant in the 1990s, resulting in the retraction of the process of opening new areas and an increase of areas in regeneration (Figure 3). The regeneration process occurs predominantly between periods when economic cycles lead to the expansion of agricultural crops, as was the case in the expansion of cotton in the 1990s after a period of decline of this crop in the microregion.

During the 2000s, the resumption of deforestation was partly driven by projects intended to revitalize cotton farming (*e.g.,* 2002 to 2005) in the southwestern portion of Bahia and in the mid São Francisco River valley (Gonçalves 2007). In the 2000s, in addition to these programs to encourage cotton cultivation, the cutting of vegetation was also caused by extractive activities, mainly the illegal production of charcoal to supply the steel industry in neighboring Minas Gerais state (Martins 2003). In the early 2000s, illegal cutting of the *caatinga* for charcoal production was denounced by the Bahia Journalists Union (Sinjorba) and the Bahia Press Association (ABI), with support from the Bahia Public Ministry (Martins 2003). According to estimates published by the magazine *Integração*, 200 trucks loaded with charcoal left the Guanambi microregion daily, coming from various municipalities in the microregion as well as from neighboring microregions. The volume of the 200 trucks corresponds to 14,400 m^3 (Martins 2003), which would mean cutting and burning approximately 200 ha of native vegetation every day. These estimates were not produced following scientific methodology, but they contribute to highlighting the level of destruction of vegetation in this part of northeastern Brazil.

Livestock have been an important driver of vegetation cutting in the Guanambi microregion in recent years, usually for establishing pastures in "*capoeiras*" (secondary vegetation in regeneration) or in areas with remaining native vegetation with no history of recent deforestation. This use pattern explains the existence of mosaics with vegetation in different stages of succession, with only rare patches of primary formations (Pereira et al. 2003). Simply quantifying the reduction in vegetation area does not reflect the full impact on biodiversity because the remaining fragments are significantly disturbed, which suggests that a large part of the remaining *caatinga* is threatened (Antongiovanni et al. 2020).

The land-use models described above indicate that the trajectory of areas with dry forests in the microregion analyzed in this study follows the same pattern found in other parts of northeastern Brazil. Vegetation in the Brazilian semiarid region has been marked by a history of degradation for agricultural purposes or for wood extraction. The latter is highly dependent on vegetation resources, and gradually degrades these resources (Ewel 1999). These conventional types of exploitation have generated degradation without providing poverty reduction or socio-environmental development.

4.2. The relationship of anthropogenic and biophysical variables to deforestation

In general, deforestation in the Guanambi microregion occurred in areas close to the main roads (federal and state highways) from 1973 to 1987 and from 2001 to 2019. Road construction gave access to previously inaccessible areas, where deforestation expanded, as reported in other parts of Brazil (Fearnside 2006; Santos et al. 2019). In the case of the interval between 1987 and 2001, the pattern of deforestation dynamics was different, where deforestation occurred mainly in areas over 11 km from the main roads. Despite the mapping of new main roads in 1987, such as state highway BA-156 (cutting through the municipalities of Caetité, Licínio de Almeida, Jacaraci and reaching Mortugaba) and the increase in stretches of federal highway BR-122 (in the northern portion of the municipality of Caetité), no change was observed in the vegetation cover around these roads due to their location in areas of accentuated relief, including mountain ranges. In addition, deforestation was already consolidated in the surroundings of some main roads when they were mapped in the 1987 satellite image, such as BA-573 (which connects to BR-030 in the municipality of Guanambi and BA-430 in the municipality of Riacho de Santana) and a section of BA-160 (which connects to BR-030 in the municipality of Iuiu). Therefore, from 1987 to 2001, deforestation occurred more through the expansion of already-deforested areas than through the opening of new roads. The fact that deforestation is driven by the expansion of already-deforested areas can be observed by the behavior of the weights-of-evidence curve, which indicates that the areas close to those classified as "other uses" had the highest weights-of-evidence values, indicating that they were more attractive to deforestation.

The weights-of-evidence contrast values demonstrate that areas with steeper slopes inhibited the occurrence of deforestation and, therefore, are the places that concentrate the largest remnants of dry forest in the Guanambi microregion. More sloping areas are less accessible and are difficult to mechanize, making them less vulnerable to deforestation (Resende et al. 2013).

As for the soil, 65% of the study area consists of the following soil types: yellow latosol (28%), haplic cambisol (20%) and haplic planosol (17%). Of these, the haplic cambisol and haplic planosol types showed positive weights-of-evidence values in all analyzed intervals.

Deforestation in 1973-1987 was attracted mainly to areas with forest formations (*i.e.,* deciduous and semideciduous montane and submontane seasonal forests). In subsequent periods, this pattern changed, and areas of contact zone between savanna and forest became more attractive for deforestation. One fact that may have contributed to this change could be that after 1987 most accessible areas with forest formations had already been cleared, and the remaining forests were in areas with steeper slopes, where the occurrence of deforestation was very low due to difficult access. Thus, contact zones became more pressured and susceptible to being cleared.

4.3. The impacts of deforestation in the semiarid portion of Bahia

Dry forests in northeastern Brazil are rich in plant and animal diversity (Garda et al. 2018; Leal et al. 2005). Cutting vegetation directly impacts plant biodiversity and the animal community due to habitat loss. Removal of vegetation in semiarid areas also impacts water resources (Albuquerque et al. 2001). Deforestation is associated with the drying up of water courses, springs, lakes and swamps, which is especially damaging in a region where water resources are already scarce. Due to the absence of rain in 5 to 6 months of the year in most of the study area, the available water resources should be protected as a priority resource since water is the main limiting factor for economic activities in the semiarid region, as well as for the life of humans and other animals. Deforestation reduces the availability of water and exacerbates the difficulties faced by populations in rural areas. It affects populations in urban areas by compromising the capture and recharge of reservoirs intended for domestic water supply. Loss of vegetation also affects the water supply to reservoirs built for irrigation in large agricultural projects. Most of the streams and rivers in the Guanambi microregion have had their courses exposed to siltation in the period since 1973, thereby reducing the volume and duration of seasonal springs, in addition to resulting in various species of fish being categorized as at risk of extinction (Brazil ICMBio 2018).

Cutting vegetation accompanied by successive degrading activities results in soil loss and desertification. About 200,000 km² of the Brazilian semiarid region is in an advanced process of desertification (Sá and Angelotte 2009; Tabarelli et al. 2018; Vieira 2015). In the driest months of the year, soil without vegetation is exposed to winds, high temperatures, and low humidity, and it is common to encounter areas of degraded pasture that resembling the surface of the moon. In areas destined for livestock, demand for pasture is higher in the dry season, and the resulting intense grazing can drastically reduce any plant cover. The different types of environmental impact associated with vegetation removal directly result in socioeconomic impacts for populations residing in the semiarid region. As in other dry-forest regions of the world, the legacy of Brazil's semiarid region needs to be better documented and protected (Tabatelli et al. 2018).

4.4. The need to protect dry forests

The dynamics of deforestation analyzed here indicate that initiatives to conserve dry forests in northeastern Brazil need to be implemented quickly because areas with remaining or little-altered vegetation are increasingly scarce and are rapidly disappearing. New protected areas are needed to ensure the maintenance of the few existing areas. Remaining areas of dry forest are especially threatened when they are on high-fertility soils and if they have a significant volume of wood per hectare, including species with high commercial value (Mooney et al. 1995; Ribeiro and Walter 1998).

In addition to conservation initiatives, inspection and command-and-control actions need to be implemented. The portions of the microregion that have flat topography and fertile soils have been almost completely cleared by wealthy cotton planters. Especially in these areas, protection of the remaining forest fragments and regeneration of some of the cleared areas require rigorous enforcement of the Brazilian Forest Code, which requires landowners to maintain (or regenerate if lacking) native vegetation in a "legal reserve" ("*Reserva Legal*" or "RL") and in "permanent preservation areas" ("*Áreas de Preservação Permanente*" or "APPs"). The "legal reserve" is an area that must be kept in native vegetation (although it can be managed), specified as 20% of each property in the *Caatinga* Biome. "Permanent preservation areas" are strips of a specified width along all watercourses, plus areas on steep slopes.

Conservation of dry forests in northeastern Brazil will not be ensured only by creating new protected areas and carrying out inspection and enforcement actions. In the case of the hilly areas where most of the remaining vegetation is located, the predominant actors are small farmers with limited economic means. Possibly the most difficult action, which is also the one that could best contribute to the conservation of dry forests in northeastern Brazil, would be to design technologies to allow rural populations to support themselves in the semiarid region while simultaneously conserving (or even restoring) vegetation resources.

The rate of deforestation in the different vegetation types referred to as "dry forests" continues to be high, both in Brazil and throughout South America (Miles et al. 2006). However, current estimates of annual deforestation are lacking for areas with dry forests in the Brazilian semiarid region. This obstacle needs to be overcome to support both inspection and conservation actions so that effective, measurable results can be achieved. The absence of monitoring of *caatinga* cutting and of adequate inspection actions reflects the low priority that is given to dry forests, especially in regions inhabited by poorer populations, as is the case of the Brazilian northeast. Although our study only addresses the southern portion of the semiarid region of Bahia, it contributes to demonstrating the need and urgency of actions to protect and conserve forests on all of Brazil's dry lands, some of which are seriously threatened with disappearing forever.

Conclusions

Cutting of vegetation advanced over the course of 46 years throughout the Guanambi microregion, in the southern portion of the semiarid region of Bahia. Deforestation was particularly intense until the late 1980s, decelerating in the 1990s to the point where deforestation was overtaken by regeneration. Vegetation cutting resumed in the 2000s, resulting in a landscape in 2019 where larger fragments of vegetation were restricted to hills and mountain ranges. Between 1973 and 2019, the area with vegetation was reduced by 614,000 ha. Studies are needed to better evaluate the consequences of cutting vegetation on the rich biodiversity in this region. The loss of vegetation highlights the need for conservation actions and the promotion of rational use of the remaining resources of the *caatinga* to allow the coexistence of human populations and the conservation of *caatinga* ecosystems.

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Supplementary Material

Cutting of dry forests in a semiarid region of northeastern Brazil

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Additional information of study area

The Brazilian semiarid region, besides being a political unit, has been classified into large landscape units and as respective geo-environmental units (Brazil EMBRAPA 2000). According to this classification the Guanambi microregion has the Sertaneja Depression and alluvial areas in the western portion, karst surfaces in the southwestern portion, reworked surfaces in the central portion and the Serra do Espinhaço mountain range, in the eastern portion (Brazil EMBRAPA 2000). The Sertaneja Depression is characterized by extensive low-lying areas with predominantly gentle-wavy relief, with residual elevations scattered across the landscape, rugged relief and extensive plateaus (Velloso et al. 2002).

Soils in the central and western portions of the study area are planosols, latosols and cambisols. In the municipality of Iuiu, in the southwestern portion of the Guanambi microregion, there are outcrops of bambuí limestone. In the eastern portion of the microregion, argisols, neosols and latosols predominate in higher areas, while at lower elevations there are rock outcrops and shallow, sandy, stony, litholic soils with medium fertility (Brazil IBGE 2019; Estado da Bahia 2001; Velloso et al. 2002).

The prevailing climate in the microregion is hot and dry with no excess water. Average temperature is above 18 °C in all months, except in a narrow zone where the average temperature varies between 15 and 18 °C in at least one month (Brazil IBGE 2019). According to the Köppen classification, in the western portion the climate is BSwh, and in elevated areas in the eastern portion it is sub-humid tropical (Aw) (Estado da Bahia 1998). Altitude in the Guanambi microregion varies from 412 to 1460 m, with altitudes of up to 600 m predominating in most of the microregion. The highest altitudes occur to the east in parts of the Serra do Espinhaço mountain range, and in Serras dos Montes Altos State Park (Farr et al. 2007).

Average total annual precipitation is 714.5 mm (range 288.4 to 1389.2 mm; n=53 years) in the central portion of the microregion (Guanambi municipality), from 808.6 mm (range 396.4 to 1250.0 mm, n=92 years) in the eastern portion (municipality of Caetité), and 837.8 mm (range 244.2 to 1343.1 mm; n=39 years) in the western portion (municipality of Carinhanha) (Brazil ANA 2019). Most precipitation in the microregion falls between October and April when the average monthly precipitation is above 50 mm in the wetter portions or between November and March in the more arid portions. The duration of the dry season, when rainfall is almost completely absent, is between 5 and 7 months depending on the different zones of the microregion (Brazil IBGE 2002). On average, rainfall occurs on 40.1 days per year (n=53 years) in the central portion, 75.5 days in the eastern portion (n=92 years) and 62.8 days in the western portion (n=55 years) (Brazil ANA 2019).

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Table S1. Description of the images used for mapping the vegetation cut in the 46-year period (1973-2019).

Year/Acquisition of Image	Landsat 1	Landsat 5 and 8
1973	Pixels with 80-m resolution (path/row 233-70, 07/28/1973; 234-70, 08/16/1973; 234-69, 07/11/1973).	--
1987	--	Pixels with 30-m resolution (path/row 218-70, 08/18/1987; 218-69, 08/18/1987 and 217-70, 07/10/1987).
2001	--	Pixels with 30-m resolution (path/row 217-70, 04/10/2001; 218-70, 09/09/2001 and 218-69, 09/09/2001).
2019	--	Pixels with 30- m resolution (path/row 218-70, 10/29/2019; 218-69, 09/27/2019 and 217-70, 09/20/2019)

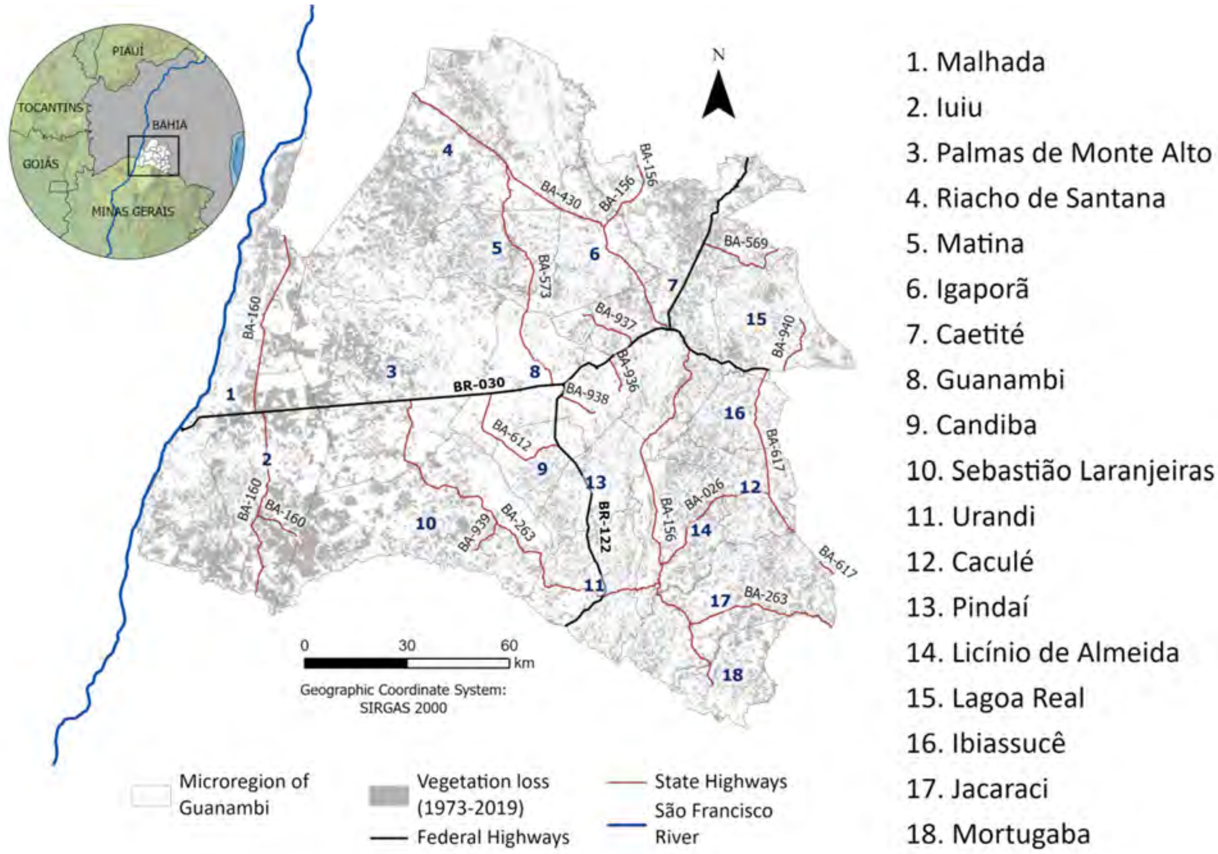

Figure S1. Spatial distribution of federal and state highways in the Guanambi microregion.

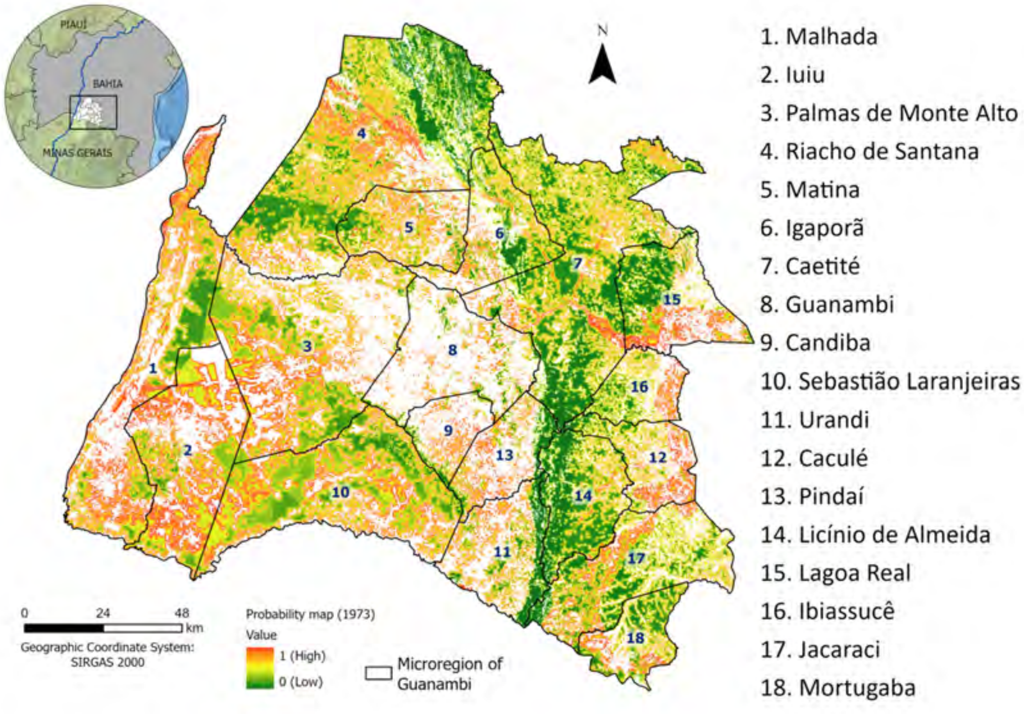

Figure S2. Probability map from 1973 indicating areas of remaining vegetation with high probability (close to 1) of being cleared and areas with low probability (close to zero). Areas with no color refer to cleared areas.

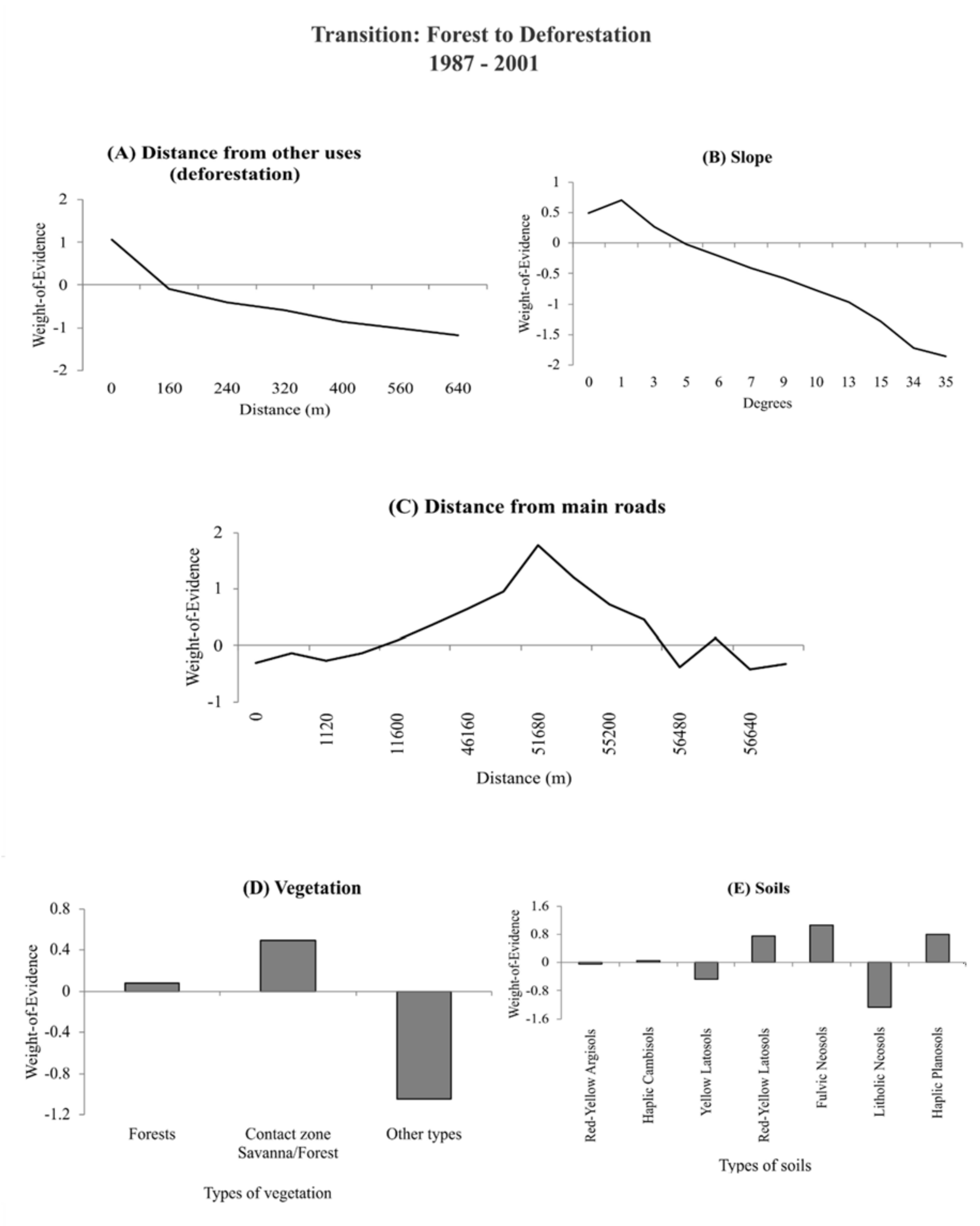

Figure S3. Values of the weights-of-evidence contrasts for the biophysical and anthropogenic variables in the period from 1987 to 2001. Values of the weights-of-evidence contrasts for the biophysical and anthropogenic variables in the period from 1987 to 2001. (A) "Other uses" refers to deforestation; (C) "Main roads" refers to a federal and state highways; (D) Forest formations represent seasonal deciduous and semideciduous forests. Contact zone is between Savanna or Seasonal Forest and Steppe-like Savanna or Seasonal Forest. Other types of vegetation refer to classes such as different types of savanna (*e.g.,* Treed savanna, Steppe-like savanna, Parkland savanna), pioneer formations, etc.

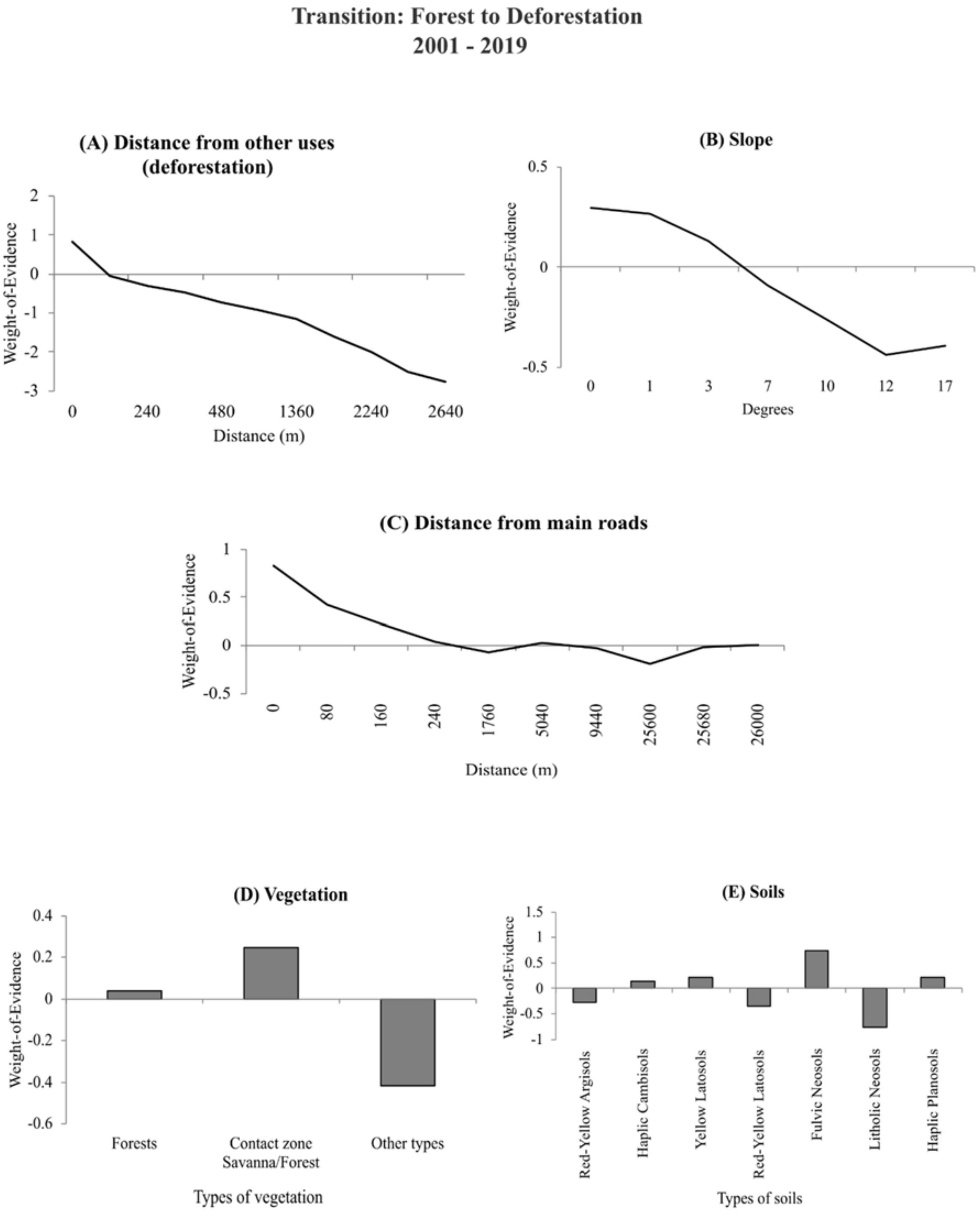

Figure S4. Values of the weights-of-evidence contrasts for the biophysical and anthropogenic variables in the period from 2001 to 2019. (A) "Other uses" refers to deforestation; (C) "Main roads" refers to a federal and state highways; (D) Forest formations represent seasonal deciduous and semideciduous forests. Contact zone is between Savanna or Seasonal Forest and Steppe-like Savanna or Seasonal Forest. "Other types of vegetation" refers to classes such as different types of savanna (*e.g.,* Treed savanna, Steppe-like savanna, Parkland savanna), pioneer formations, etc.