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Are Land Use and Cover Changes and Socioeconomic Factors Associated with the Occurrence of Dengue Fever? A Case Study in Minas Gerais State, Brazil

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Abstract: Several studies have already demonstrated the relationship between the loss of natural habitats and the incidence of diseases caused by vectors, such as dengue, which is an acute fever disease that is considered a serious public health problem. The aim of the present study was to investigate the relationship between the number of dengue cases and land use and cover changes (LUCC) and socioeconomic and climatic factors by municipality, using the state of Minas Gerais as a case study. For this, secondary data obtained from openly available sources were used. Natural vegetation cover data were obtained from the MAPBiomas platform and dengue occurrence data from the Ministry of Health, in addition to eight socioeconomic parameters from the Brazilian Institute for Geography and Statistics and precipitation data from the Brazilian Agricultural Research Corporation (EMBRAPA, Sete Lagoas, Minas Gerais). Between 2015 and 2019, 1,255,731 cases of dengue were recorded throughout the state of Minas Gerais, ranging from 0 to 227 per thousand inhabitants between municipalities. The occurrence of dengue was distributed throughout all regions of Minas Gerais and was associated with LUCC and socioeconomic factors. In general, municipalities with a net loss of natural vegetation, predominantly located in the Cerrado biome, had the highest number of dengue cases in the studied period. Additionally, the occurrence of dengue was associated to three socioeconomic parameters: population density, human development index (both positively), and Gini inequality index (negatively). These results indicate that, contrary to expectations, municipalities with better social conditions had more dengue cases. Our study indicates that natural vegetation is, directly or indirectly, involved in the ecosystem service of dengue control, despite the occurrence of this disease being affected by multiple factors that interact in a complex way. Thus, policies towards reducing deforestation must be complemented by a continuous investment in public health policies and a reduction in social inequalities to efficiently control dengue fever.

Keywords: vector-borne diseases; deforestation; ecosystem services; public health; epidemiology; disease control

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1. Introduction

Natural ecosystems have been degraded at alarming rates in recent decades, leading to numerous direct and indirect consequences at different scales [1–3]. In tropical regions, deforestation and forest degradation are mainly caused by the expansion of agricultural activities, such as cattle raising and monocultures in large areas [4]. These changes in land use and land cover negatively affect ecosystem functioning [5], reducing or eliminating the provision of important environmental services, such as pollination and the control of agricultural pests and disease vectors [6].

Several studies have already demonstrated the relationship between the loss of natural habitats and the incidence of vector-borne diseases such as dengue, malaria, leishmaniasis, and Chagas disease [7–11]. In fact, the expansion of urbanization promotes closer contact among humans, domestic animals, and wild reservoirs of viruses and protozoa, among others [12]. The removal of forests drastically alters local and regional climatic conditions, in addition to intensifying erosion processes and changing the quantity and quality of water, which can affect the availability of microhabitats for the reproduction of several species of vectors, such as mosquitoes [13,14]. Deforestation also affects the composition of plant and animal communities, changing the availability of resources and vector predators and pathogen reservoirs [3,15]. However, these multiple interactions are extremely complex, and the effects of deforestation on disease vectors vary according to the biology of different species.

Despite well-documented evidence, the relationship between deforestation and vector-borne diseases is still controversial, as there is often a simplification of ecosystems composed of pathogens-vectors-hosts [16–18]. In addition, deforestation is strongly driven by government development policies and subjected to pressure from different national and international economic sectors [14,19,20], which generates intense public debate around the evidence of the relationship between deforestation and extremely debilitating diseases such as dengue, malaria, and, more recently, COVID-19 [21]. Finally, several socioeconomic factors interact with biological aspects in determining the occurrence of pathogenic diseases. The nexus between environmental degradation, poverty, and disease is also widely studied and controversial [22]. In fact, unplanned urban growth in deforested areas can favor the proliferation of insect vectors [23]. Low socioeconomic indicators are also associated with insufficient basic sanitation, such as inadequate solid waste disposal and sewage treatment, in addition to inefficient health care systems [13,14,17,24].

In Brazil, several studies have investigated the connections between deforestation and vector-borne diseases in different regions, such as malaria and dengue in the Amazon [25], dengue in Rio de Janeiro [24,26–28], and leishmaniasis in São Paulo [29,30]; a study carried out by Silva et al. [31] demonstrated that the increase in the degradation of the Cerrado is directly related to the increase in the incidence of dengue in the region. The study points out that if deforestation continues at the same speed until 2030, it is very likely that the Cerrado regions will have a significant increase in dengue cases.

Dengue is an acute fever disease caused by a virus (flavivirus) and considered a serious public health problem in the world, especially in tropical countries, where the environmental conditions favor the development and proliferation of the mosquito vector *Aedes aegypti* [32]. The vector exhibits heterogeneous, adaptable, and unpredictable population dynamics. It is believed that mosquitoes have undergone adaptations that have allowed them to survive in areas with long periods of drought [33], but with human influence, habitats for reproduction are provided throughout the year, ensuring large population sizes in a short period of time [34].

Dengue has a seasonal pattern in Brazil, with a higher incidence of cases in the first five months of the year, when rainfall is more intense and humidity is high [35–37]. Until the mid-1990s, Southeast Asia was the region of the world most affected by dengue. From then on, the countries of Central and South America began to stand out in this scenario and started to contribute with more than half of the notified cases of the disease across the globe [38–41]. Dengue fever is considered as a reemerging endemic or pandemic disease [4,38], and several outbreaks have occurred in Brazil in recent decades, often in urban areas [42], with prevention campaigns focused on eliminating residential water reservoirs and applying ultra-low-volume insecticides [43]. Recently, modern control approaches have arisen, such as the mass release of lab-produced sterile male mosquitoes [44] and vaccine development [45]. However, a better understanding of the relationship between the incidence of dengue and deforestation is important for policies to control this disease based on a large-scale ecosystem services approach, with multiple benefits in terms of environmental health.

Thus, the objective of the present study was to determine the factors associated with the spatial variation in the occurrence of dengue fever, using the state of Minas Gerais in Brazil as a case study. Despite this regional approach, it is important to highlight that our analyses cover an area of 586,528 km^2, which is larger than France. We performed non-spatial regional regression models [46] to explore the relationship between the number of dengue cases and land use and cover changes (LUCC), using eight socioeconomic parameters and one climatic factor (precipitation) and using 853 municipalities as analytical units. Such an approach is adequate because the municipality is the basic level of decision-making in Brazil, which makes trends and patterns of LUCC in the municipality very useful for policy design. In addition, it allows the incorporation of a greater number of explanatory variables obtained from census data that include human population, well-being indicators, and economic variables.

2. Materials and Methods

2.1. Study Area

The state of Minas Gerais is located in southeastern Brazil (Figure 1), with a population of approximately 21 million inhabitants and is the fourth largest federative unit in territorial extension, occupying 6.9% of the Brazilian territory (Brazilian Institute for Geography and Statistics—IBGE) [47]. It has three predominant climate types: tropical, mountain tropical, and semi-arid. The climate presents a unique variability, ranging from a Cwb according to the Köppen climate classification (temperate with cold winters and mild summers) in the south of the state to BSwh (characterized as semi-arid) in the extreme north and northeast of the state [48,49]. Three Brazilian biomes occur in Minas Gerais: the Cerrado (a savannic ecosystem), the Caatinga (composed of tropical dry woodlands), and the Atlantic Rain Forest. The Cerrado has a total area of approximately 2.04 million km^2, but due to deforestation, less than 50% of the original ecosystems are still intact. The Atlantic Rain Forest is located in the southeast of the state in very fragmented areas due to the proximity to large urban centers. The Caatinga occurs in the north of the state, and about 30% to 50% has undergone anthropogenic changes [50].

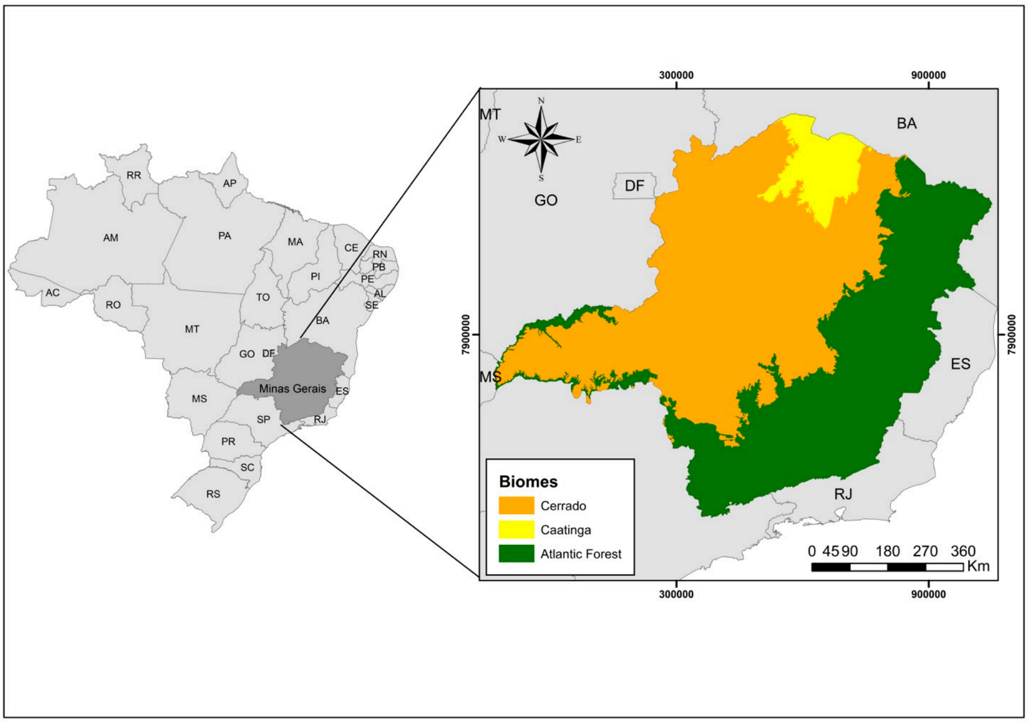

Figure 1. Brazilian political map, with emphasis on the state of Minas Gerais and its three biomes. Source: Brazilian Institute for Geography and Statistics [49].

2.2. Obtaining Data

2.2.1. Changes in Land Use and Cover

Land use and land cover data were obtained from the MapBiomas website, which is an initiative of the Greenhouse Gas Emissions Estimation System of the Climate Observatory (https://plataforma.seeg.eco.br/, accessed on 5 March 2024) and is produced by a collaborative network of co-creators formed by non-governmental organizations, universities, and technology companies. MapBiomas information is organized by biomes and cross-sectional themes [51]. Data on vegetation cover and the main Brazilian vegetation formations are available on the website (https://mapbiomas.org/, accessed on 15 December 2023), along with maps of vegetation cover, statistical data, and the mosaic of Landsat images for download. The high-resolution maps (30 m pixels resolution) are based on machine-learning algorithms and Landsat satellite images are available through the Google Earth Engine platform [51].

For each municipality, natural vegetation cover (forests, savannas, and other natural vegetation) was obtained in 2009 and 2019, the most recent year available at the beginning of this study. We considered that a period of 10 years is sufficient for significant changes in land use and cover in Minas Gerais [52], which could affect the occurrence of dengue between 2015 and 2019. Subsequently, the percentage of natural vegetation cover in each municipality was calculated, using the municipal area obtained from the Brazilian Institute for Geography and Statistics [53]. In addition, we calculated the percentage net change in natural vegetation cover using the formula: $[(\text{Area in 2009} - \text{Area in 2019})/\text{Area in 2009}] \times 100$. Thus, negative values indicate deforestation (net loss of vegetation cover in a municipality), while positive values indicate regeneration (net gain in vegetation cover in a municipality).

2.2.2. Dengue Occurrence

Dengue cases were obtained for each municipality in Minas Gerais from the Brazilian Ministry of Health database, available at the DataSUS website (https://datasus.saude.gov.br/, accessed on 13 July 2021), where all data related to disease notifications (of any nature) are available through the Tabnet platform (https://datasus.saude.gov.br/informacoes-de-saude-tabnet/, accessed on 13 July 2021). These data are collected by Brazilian municipalities and sent to regional (state) health departments, from where they are sent to the Secretary of Health of each state and finally aggregated by the Ministry of Health to be made available for consultation. Dengue cases were obtained for the five most recent years available at the beginning of the study (2015 to 2019) in order to account for the variations that occurred during outbreaks of this disease in certain years.

2.2.3. Socioeconomic and Climatic Factors

We obtained eight socioeconomic parameters that are potentially associated with the occurrence of dengue for the 853 municipalities in the state of Minas Gerais (Table 1). Data for seven parameters were obtained from different IBGE databases (2021): (1) population density [47]; (2) gross domestic product (GDP) per capita (2018); (3) Municipal Human Development Index—HDI (2018), which combines three dimensions—longevity, education, and income—and varies from 0 (low) to 1 (high development); (4) Gini Inequality Index (2010), which is based on income and varies from 0 (no income inequality) to 1 (complete income inequality); (5) total urban area (2019); (6) percentage of people vulnerable to poverty (2018); and (7) percentage of people in households with inadequate water supply and sewage system (2018). Data on (8) annual government investment in health per municipality were obtained from the Information System on Public Health Budgets (SIOPS) in the DataSUS website (http://siops-asp.datasus.gov.br/CGI/tabcgi.exe?SIOPS/serhist/municipio/indicMG.def, accessed on 13 July 2021). Values in Brazilian reais were obtained for five years (2015–2019) and summed to calculate the total investment per municipality during the same period of dengue incidence in the present study. Finally, the average annual precipitation (mm) per municipality was obtained from Guimarães et al. [54] and based on a temporal series lasting from 15 to 70 years, depending on the state region.

Table 1. Socioeconomic and climatic parameters (average values per municipality; n = 853) potentially related to changes in land use and the number of dengue cases in Minas Gerais state, Brazil. See text for details on the data source of each variable.

Parameter	Average Value (±Standard Deviation)
Annual precipitation (mm)	1282.29 ± 228.75
Gini Index	0.473 ± 0.05
Health expenses per capita (Brazilian reais)	3924.46 ± 1574.60
Households with inadequate water supply and sewage system (%)	3.9 ± 5.16
Human Development Index	0.668 ± 0.05
Per capita GDP (Brazilian reais)	19,993.18 ± 22,124.84
Population density	72.08 ± 339.8
Vulnerability to poverty (%)	40.70 ± 15.69
Total urban area (km^2)	424.83 ± 1376.2

2.2.4. Statistical Analysis

The relationship between the number of dengue cases per capita (response variable) and the percentage of net change in natural vegetation cover, the eight socioeconomic parameters described previously, and precipitation (10 explanatory variables in total) in each municipality was determined using a generalized linear model (GLM). The number of dengue cases was summed in each municipality for five years (2015–2019) and divided by the size of the municipal population in 2021 [47] to obtain the number of cases per 1000 inhabitants. The complete model was constructed with Poisson error distribution because our data did not follow a Gaussian distribution, and further simplified stepwise by removing non-significant variables. The minimum adequate model was subjected to residual analysis to verify the adequacy of the error and corrected to a quasiPoisson distribution, with link function Log (y). Model construction and analysis were conducted using R software, version 4.0.0 [55].

3. Results

3.1. Occurrence of Dengue in Minas Gerais State

Between 2015 and 2019, 1,255,731 cases of dengue were registered throughout the state of Minas Gerais. In absolute numbers (considering the five years together), the number of cases ranged from 0 (in 4 municipalities) to more than 10,000 (in 9 municipalities), especially in those with the largest total population (Figure 2A). Belo Horizonte (the state capital) had the highest number of cases, with 290,336. However, the number of cases per thousand inhabitants was high in several small municipalities, ranging from 0 (in 5 municipalities) to more than 100 (in 24 municipalities), reaching 227.51 in the municipality of Pequi, located at 120 km from the capital of Minas Gerais (Figure 2B). The vast majority of municipalities had up to 50 cases in total and up to 11 cases per 1000 inhabitants (Figure 3A,B) from 2015 to 2019. The occurrence of dengue was distributed across all regions of Minas Gerais, but municipalities in the south and northeast of the state had the lowest number of cases (Figure 4). The temporal variation of dengue cases shows the occurrence of two outbreaks in five years, in 2016 and 2019 (Figure 3B). The average per capita number of cases per municipality reached 11.4^{-3} in 2016 and 9.97^{-3} in 2019 (Figure 5A). The total number of cases in the entire Minas Gerais state reached 388,339 in 2016 and 357,936 in 2019 (Figure 5B).

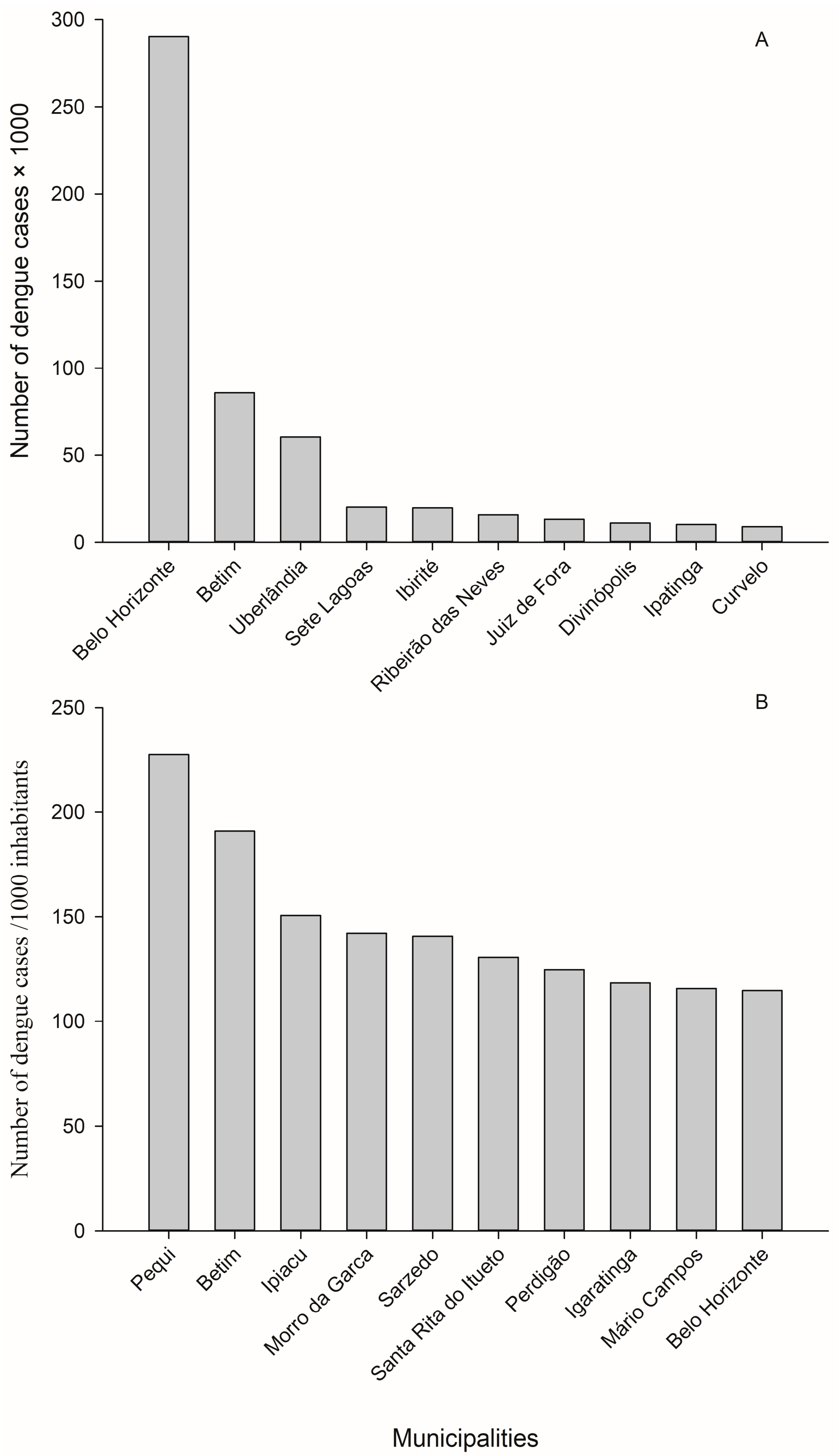

Figure 2. (**A**) Ten municipalities with the highest absolute number of dengue fever cases in five years, from 2015 to 2019; (**B**) ten municipalities with the highest number of dengue cases per one thousand inhabitants in the same period.

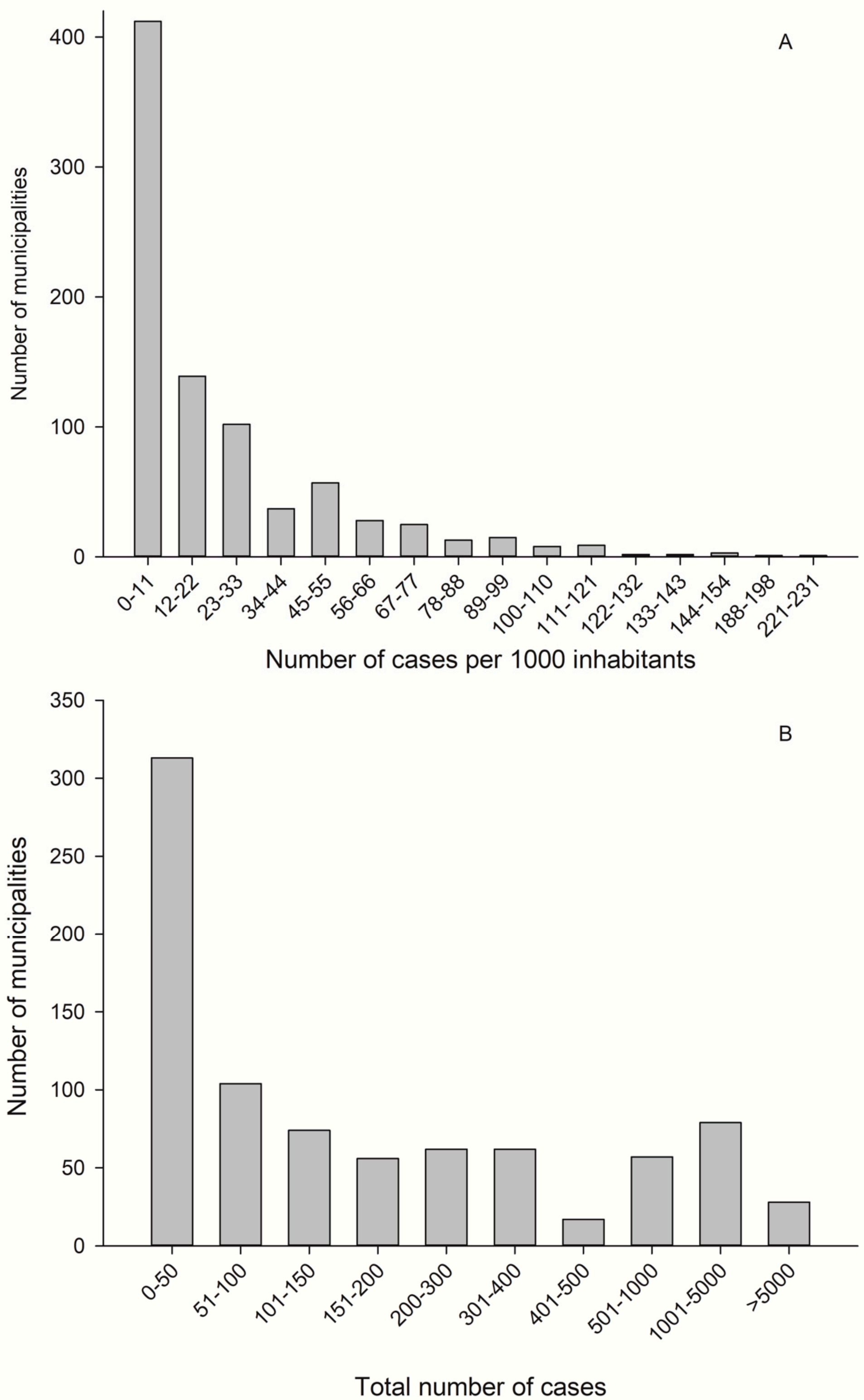

Figure 3. (**A**) Number of municipalities in each class of number of dengue fever cases per 1000 inhabitants in the state of Minas Gerais from 2015 to 2019; (**B**) number of municipalities in each class of absolute number of dengue fever cases during the same period.

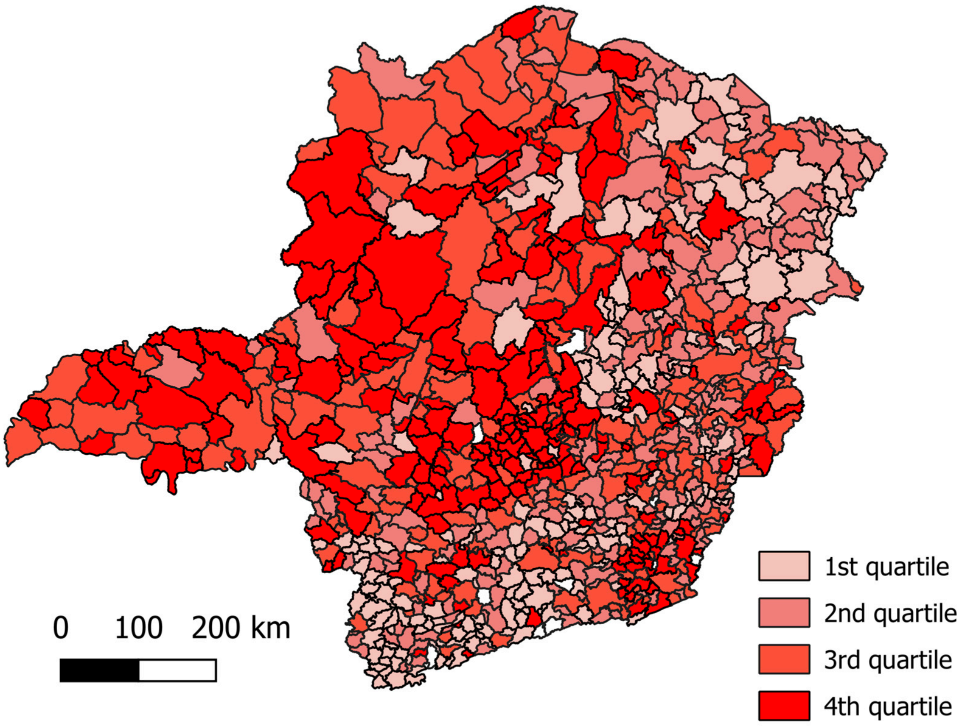

Figure 4. Map of the number of dengue cases per 1000 inhabitants in quartiles for the 853 municipalities of Minas Gerais from 2015 to 2019. Municipalities in the first quartile presented less than 2.9 cases; in the second quartile, municipalities with 2.9 to 11.63 cases; in the third quartile, from 11.64 to 31.23 cases; and in the fourth quartile, between 31.25 and 227.5 cases.

3.2. Changes in Land Use and Land Cover

The MapBiomas data indicated that natural vegetation cover varied widely between municipalities in Minas Gerais, from 4.85 to 97.4% in 2009 and from 6.29 to 96.3% in 2019. On average, natural vegetation cover increased slightly, from 34 ± 20.2% in 2009 to 35.7 ± 19.7% in 2019. Of the 853 municipalities, 341 had a net loss of natural vegetation between 2009 and 2019, with 5 losing more than 200 km^2 of vegetation during this period (Figure 6B). The total net loss in 10 years in these municipalities reached −8240.74 km^2. The remaining 512 municipalities had a net gain in natural vegetation, with 6 of them gaining more than 100 km^2 (Figure 6B). The total gain in vegetation cover was +6732.57 km^2.

Between 2009 and 2019, most municipalities had net changes in vegetation cover ranging from −10 to +10% (Figure 7). Few municipalities had a high percent loss of natural vegetation, as is the case of Glaucilândia (31.6%; another 6 municipalities had losses above 20%). A larger number of municipalities (63) had expressive percent gains in natural coverage, in some cases reaching 78%, as in Tumiritinga. Higher percentage changes were generally observed in municipalities with a smaller total area. In general, it is possible to notice a clear spatial pattern of changes in vegetation cover, with greater net gain in the center, east, and southeast of Minas Gerais state, which are regions predominantly covered by the Atlantic Rain Forest. In the west, north, and northwest, where the Cerrado and Caatinga predominate, most municipalities had a net loss of vegetation cover (Figure 8).

3.3. Socioeconomic and Climatic Factors

Basic sanitation data showed that, on average, a low proportion of households have inadequate sanitary sewage and poor distribution of drinking water (3.39%) in the municipalities of Minas Gerais (Table 1). The average HDI per municipality was lower than the global average (0.702) and the Brazilian average (0.765) [47]. Only two municipalities in Minas Gerais had an HDI greater than 0.8: Belo Horizonte (0.81) and Nova Lima (0.813). The vast majority of municipalities with the lowest HDI were located in the north of Minas

Gerais (Supplementary Figure S1), and São João das Missões (0.529) had the lowest HDI. The Gini inequality index for the Minas Gerais state was 0.473, which is lower than that observed for Brazil as a whole (0.640) [56]. Only 13 municipalities had values greater than the national average of inequality, with Jequitibá as the most unequal municipality in the state, with a Gini index of 0.78, and Córrego Fundo the least unequal, with 0.31 (Figure S2). The average annual precipitation varied from 650 mm in Porteirinha, in the semi-arid north of Minas Gerais, to approximately 2000 mm in Bocaina de Minas, in the mountainous south of the state. The per capita government investment in health per municipality varied ten-fold, from BRL 1713 in Itaipé to BRL 17,532 in Serra da Saudade.

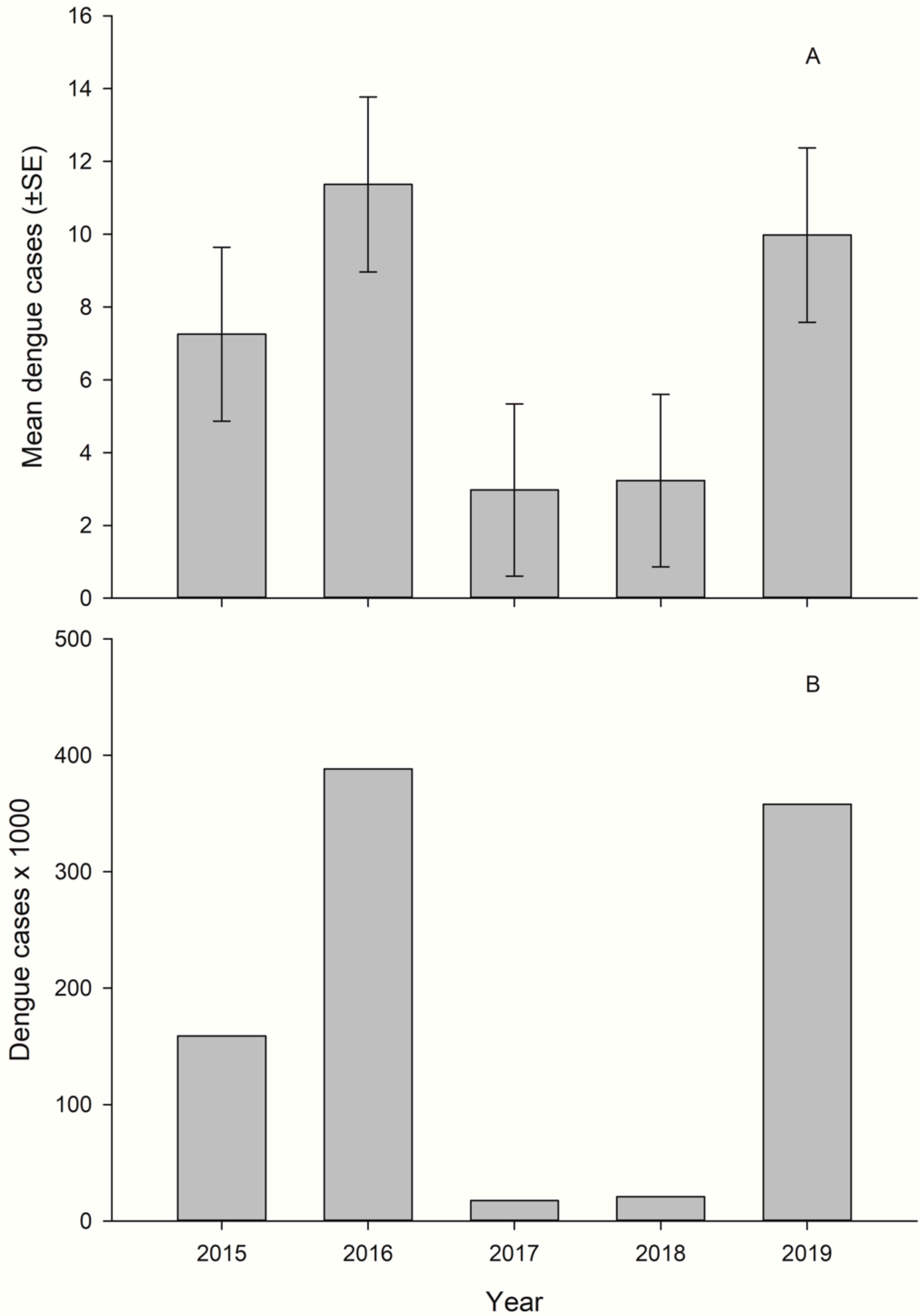

Figure 5. (**A**) Mean per capita number of dengue cases (×1000) per municipality between 2015 and 2019 (n = 853); (**B**) total number of dengue cases considering the entire state of Minas Gerais during the same period.

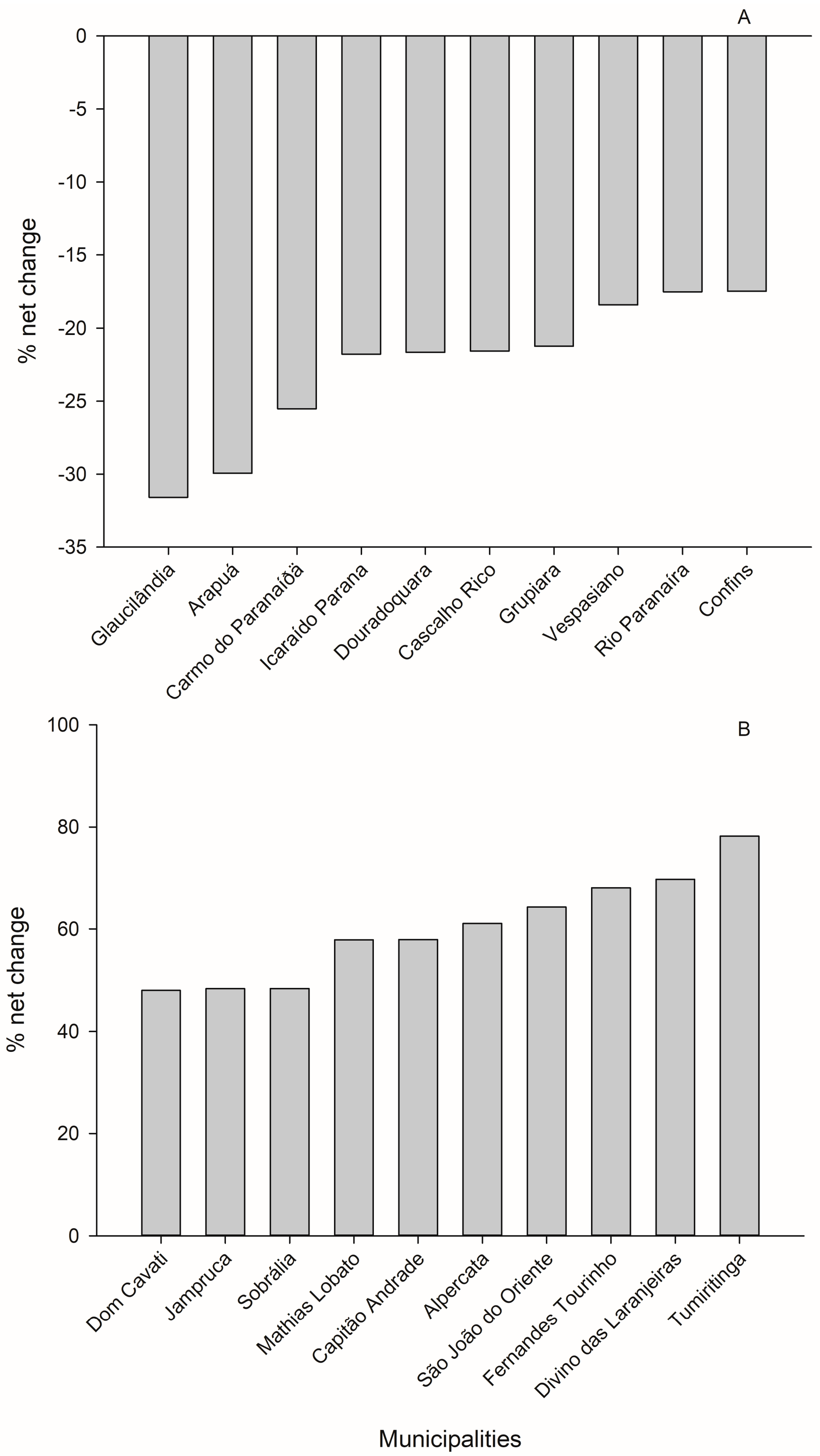

Figure 6. (**A**) Ten municipalities with the highest net loss of natural vegetation from 2009 to 2019; (**B**) ten municipalities with the highest net gain in vegetation in the same period.

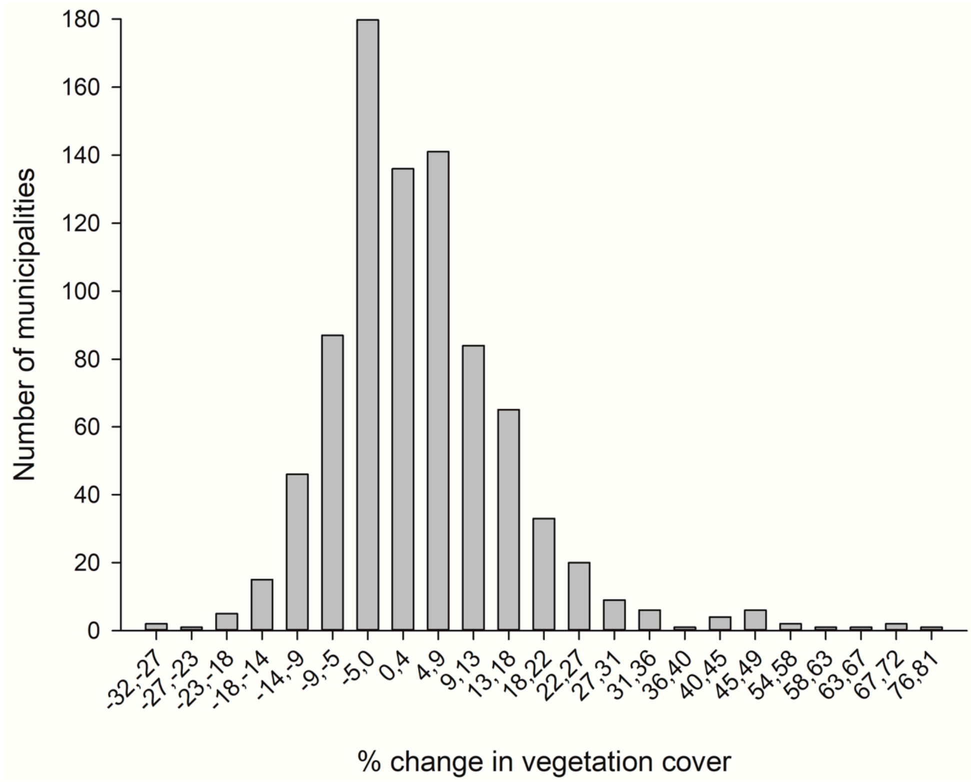

Figure 7. Number of municipalities in each class of net changes in natural vegetation cover from 2009 to 2019 in the Minas Gerais state (n = 853). Range values in each class are separated by commas (e.g., −32% to −27%). Negative values indicate net loss of vegetation cover (i.e., deforestation) and positive values indicate net gain (i.e., regeneration) of vegetation cover.

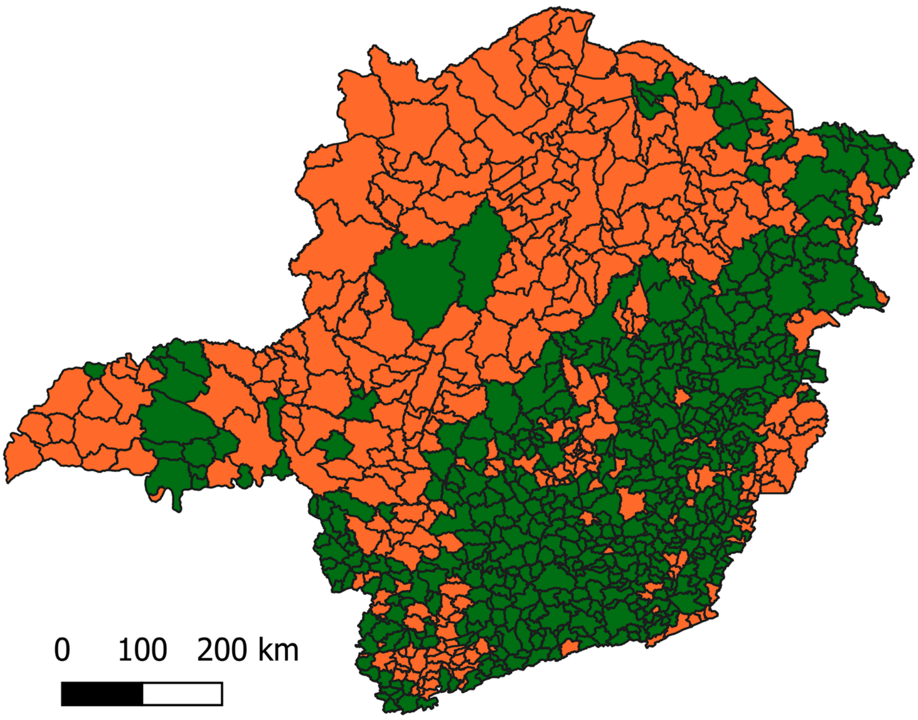

Figure 8. Changes in land use and cover in the 853 municipalities of the Minas Gerais state from 2009 to 2019. Municipalities in orange had a net loss of vegetation and municipalities in green had a net gain in vegetation during this period.

3.4. Factors Associated to Dengue Occurrence

The GLM analysis indicated that the number of dengue cases is significantly associated with the percentage of net change in vegetation cover in the municipalities of Minas Gerais (Figure 9A). In general, municipalities with a net loss of vegetation cover between 2009 and 2019 had a greater number of dengue cases between 2015 and 2019. On the other hand, municipalities with a net gain in vegetation cover had fewer occurrences of dengue fever in the studied period. Three out of eight socioeconomic indicators were significantly associated with dengue occurrence (Table 2; Figure 9). The highest number of dengue cases occurred in municipalities with lower inequality (Figure 9B), higher population density (Figure 9C; Figure S3), and higher HDI (Figure 9D). Contrary to expectations, the occurrence of dengue was not associated with indicators focused on basic sanitation in our analysis.

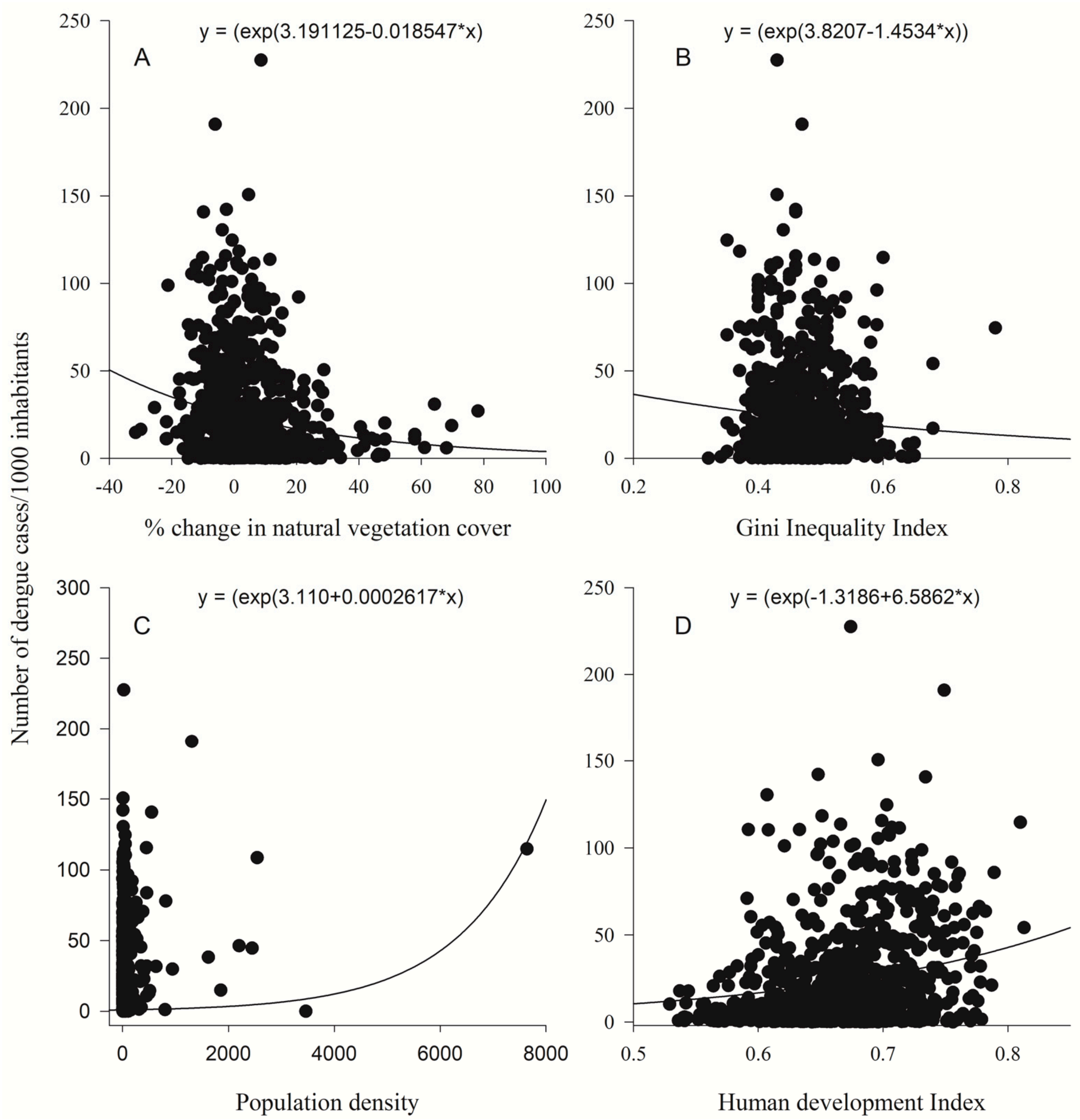

Figure 9. Relationship between number of dengue cases per municipality in Minas Gerais (n = 853) and (**A**) percentage of net change in vegetation cover, (**B**) Gini inequality index, (**C**) population density, and (**D**) Human Development Index (HDI).

Table 2. Generalized linear model (GLM) analysis to determine the relationship of the number of cases of dengue per 1000 inhabitants with the net change in vegetation cover and socioeconomic and climatic parameters in 853 municipalities in Minas Gerais, Brazil. The complete model with 10 parameters is shown. * % of the total variance explained for each variable ((variance explained by each variable/total variance) × 100).

Response Variable	Parameter	Explained Variance (%) *	DF	Deviance	F	*p*
Number of dengue cases	% change in natural vegetation	1.483	808	411.48	13.12	<0.001
	Gini index	0.816	814	160.15	5.19	<0.001
	Health expenses	0.009	815	2.33	0.07	0.78
	Households with inadequate water supply and sewage system (%)	0.191	811	113.82	3.63	0.57
	Human Development Index	8.893	813	1677.75	53.52	<0.001
	Per capita GDP (Brazilian reais)	<0.001	809	0.21	6.0	0.93
	Population density	1.92	817	461.16	14.71	<0.001
	Precipitation	0.002	816	0.47	0.01	0.90
	Total urban area (km^2)	0.098	810	9.34	298.0	0.59
	Vulnerability to poverty (%)	0.398	812	19.61	625.0	0.43

4. Discussion

The present study, to our knowledge, is the first to analyze the relationship between dengue occurrence and deforestation simultaneously, considering all municipalities in the state of Minas Gerais. Our results demonstrated a positive relationship between these two variables, suggesting that natural vegetation is, directly or indirectly, involved in the ecosystem service of dengue control. However, population density and socioeconomic factors were also associated with the number of dengue cases per municipality in a complex relationship that may also involve climatic factors not evaluated in the present study. Despite this, determining the effects of deforestation on a disease with high prevalence and strong socioeconomic impacts is extremely important for the design of integrated environmental health policies throughout Brazil.

Despite a high occurrence of dengue in all regions of Minas Gerais between 2015 and 2019, a lower number of cases were observed in the south and northeastern regions (see Figure 4), which are quite diverse from a climatic and socioeconomic point of view. Such regions are found mainly in the Atlantic Forest biome (see Figure 1), as delimited by the IBGE Biome Map [49,50], which has a special protection regime defined by the Atlantic Forest Law (Federal Law 11428/2006; https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2006/lei/l11428.htm, accessed on 7 March 2024). According to this law, deforestation is only permitted In areas in the early stage of natural regeneration or in cases of public utility and social interest. This restriction on forest conversion may be related to the greater gain in vegetation in most municipalities in this biome in Minas Gerais between 2009 and 2019, being one of the factors responsible for the lower occurrence of dengue in regions of the Atlantic Rain Forest.

The same climatic and socioeconomic diversity is observed for the regions of Minas Gerais with the highest occurrence of dengue, such as the west, northwest, north, and central regions (see Figure 4). The Cerrado and Caatinga biomes predominate in these regions [49,50], where land use is governed by the Native Vegetation Protection Law (Federal Law 12651/2012; https://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm, accessed on 7 March 2024). In these cases, deforestation of up to 80% of each rural property is permitted, with only 20% being kept as a "legal reserve". In the northern region of Minas Gerais, seasonally dry, deciduous forests are considered as part of the Atlantic Forest biome by the Decree 6660/2008 but suffer high rates of deforestation even with this protection [57,58]. Several studies have already demonstrated the relationship between the incidence of arthropod-borne diseases and deforestation [6,17,25,59,60], including dengue in other regions of Brazil [4,24,27,61,62]. MacDonald and Mardoqueu [63] used the regionalization of areas in the Amazon to more effectively identify the relationship between malaria cases and deforestation, making clear the importance that native areas have for local public health. These researchers reported that, even in the most pessimistic scenarios, the reduction in the number of infectious disease cases in tropical regions will only happen through an extreme reduction in deforestation and the implementation of public policies aimed at mitigating, monitoring, and conserving natural vegetation. Furthermore, urbanization without minimal infrastructure (for example, access to basic sanitation), associated with the change in habits and cultural customs of the Amazonian population, created ideal conditions for *Aedes aegypti*, the main vector of dengue, chikungunya, and Zika virus [25].

In the specific case of dengue, some studies at different spatial scales have investigated the relationship between the incidence of dengue and deforestation in Brazil, with contrasting results. Moura et al. [64] observed that, for the state of Rio de Janeiro, the number of dengue cases between 2001 and 2007 was positively correlated with the extent of fires and the absence of basic sanitation. Silva et al. [31], considering the entire Cerrado biome, found a positive relationship between the occurrence of dengue and deforestation between 2001 and 2019. These authors also projected, through simulation models, an increase in the number of dengue cases by 2030 for the states of Minas Gerais, São Paulo, and Mato Grosso due to the increase in deforestation. However, Kalbus et al. [65] found no relationship between the incidence of dengue and deforestation in the state of Amazonas, with the number of cases between 2007 and 2017 influenced only by access to basic health care. This lack of relationship was also found by Morais [66] for 67 municipalities in the Atlantic Rain Forest of Minas Gerais state. These conflicting results, depending on the region and period of study, reflect the fact that the incidence of dengue is related to multiple factors that interact in a complex and non-linear way, as indicated in a recent systematic review carried out by Sousa et al. [67]. These authors analyzed 35 studies published in Brazil and concluded that several environmental, socioeconomic, and climatic variables affect the number of dengue cases. There is an urgent need to expand the debate between the health relationship and environment, since the effects on human health arising from environmental changes are serious [68].

Our analysis also showed that the occurrence of dengue was higher in municipalities with a lower Gini inequality index and higher HDI, contrary to what we expected. Social factors can act as disease facilitators, including dengue [69]. Dengue control is hampered by demographic growth, inadequate urban infrastructure, and insufficient medical and health services. Furthermore, basic sanitation is an important factor, as it increases the number of breeding sites, favoring the proliferation of the mosquito vector [70,71]. As in the case of deforestation, studies carried out in Brazil have not shown a consistent pattern regarding which socioeconomic factors most strongly influence the number of dengue cases. However, this disease is usually positively affected by a high inequality in income distribution and low education [67,72–74]. Despite this, Morais [66] found a greater number of cases in municipalities with a higher GDP in the Atlantic Forest of Minas Gerais, suggesting that, often, even richer municipalities do not prioritize basic sanitation and health care. In the present study, a significant part of the municipalities with good socioeconomic indicators showed high deforestation, such as the west and central-west regions and the Metropolitan area of the state capital (Belo Horizonte), the opposite being observed for the poorer northeastern region (see Figure S4). Thus, concomitant strategies for controlling deforestation and reducing social inequalities are necessary to control dengue in Minas Gerais municipalities.

Climatic factors are also frequently related to the occurrence of mosquito-borne diseases, but precipitation was not significantly associated to the number of dengue cases in our analysis. Temperature was not included in the present study due to difficulties in obtaining this variable for all municipalities in Minas Gerais (e.g., [71]). Humidity and temperature play a fundamental role in the biological cycle of mosquito vectors, consequently exerting a great influence on the risk of dengue transmission [75–77]. In their review, Sousa et al. [67] found that precipitation and temperature positively affected the number of dengue cases in more than half of the articles analyzed, among several climatic parameters having been evaluated. Alves [71] demonstrated that municipalities in Minas Gerais with lower temperatures had fewer cases of dengue between 2008 and 2012, although the meteorological variables that affected the incidence of dengue differed between the years of study. In fact, it is possible to observe a lower occurrence of dengue in higher altitude regions, such as Serra da Canastra and Serra do Espinhaço, where temperatures are also lower [78]. In this sense, deforestation can directly cause an increase in the number of dengue cases, as demonstrated by our results; and indirectly, since deforestation is one of the main causes of climate change and increase in global temperature [79,80]. In fact, several studies carried out with climate models in the last decade in Brazil predicted an expansion of the occurrence of dengue fever to colder regions [42,81,82]. This synergy between regional (deforestation) and global (climate) effects can lead to a drastic increase in dengue cases, with severe social and economic consequences for Brazil.

5. Conclusions

Our results demonstrated that the loss of vegetation cover and socioeconomic factors are related to a greater occurrence of dengue in the municipalities of the Minas Gerais state. However, we acknowledge that longer time series analyses considering multiple temporal and spatial interactions, including other climatic variables, such as temperature variation and seasonality, are necessary to more robust conclusions on the drivers of dengue occurrence that could be generalized to larger scales. Despite the complex interaction between LUCC, climatic conditions, and socioeconomic factors, it is possible that public policies to reduce deforestation, such as the Atlantic Forest Law, can also help reducing the incidence of vector-borne diseases. This type of strategy, which can be applied in the Brazilian context as a whole, would have a double positive effect on dengue control in the long term, as they also contribute to mitigating regional temperature warming, restricting the spread of this disease to higher altitude, colder regions. The environmental service provided by natural vegetation in the control of infectious diseases must be complemented by a continuous investment in public health policies and a reduction in social inequalities, requiring an intersectional approach joining multiple institutions from different sectors of society.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources13030038/s1, Figure S1: Human Development Index; Figure S2: Gini inequality index; Figure S3: Population; Figure S4: Per capita income.

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