Title: Beyond the green: socioeconomic and climatic pressures on native vegetation in the Araguaia Biodiversity Corridor

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Highlights

- Native vegetation is strongly shaped by climate, GDP, and human population density;
- Higher annual precipitation and GDP predict greater vegetation cover;
- Human population density is a major driver of vegetation loss across the corridor;
- A novel Socioenvironmental Pressure Index identifies priority areas for conservation, restoration, and governance;
- Results support targeted, place-based conservation and restoration policies.

Abstract

This study examines how climatic and socioeconomic variables influence native vegetation cover across 108 municipalities within the Araguaia Biodiversity Corridor, an ecologically strategic region in central Brazil that connects Amazonian and Cerrado biomes and supports habitat continuity for wide-ranging species such as jaguars (*Panthera onca*). The corridor was spatially defined as a 40 km-wide buffer along the Araguaia River (20 km on each side), based on ecological connectivity principles and recent legislative proposals (e.g., PL 909/2024). We first characterized the municipalities based on land use, climate, and socioeconomic indicators. On average, 55.3% of municipal territory lies within the corridor, and native vegetation covers 46.5% of municipal land, with values ranging from less than 15% to over 90%. Using linear modeling, we assessed the effects of annual precipitation, Gross Domestic Product (GDP), human population density, number of rural properties, and average property size. Results indicate that precipitation and GDP are positively associated with vegetation cover, while population density shows a strong negative relationship. Additionally, municipalities with larger and more numerous rural properties tend to retain greater native vegetation. To translate these dynamics into policy-relevant metrics, we developed a Socioenvironmental Pressure Index (SPI) based on model residuals. The SPI highlights municipalities where vegetation cover is significantly lower, or higher, than expected. High-

SPI areas may require targeted restoration, land-use regulation, or enforcement actions, whereas low-SPI areas may reflect resilience or effective local governance. These findings support place-based conservation planning and inform ongoing legislative efforts to formalize the Araguaia Corridor, emphasizing the need to integrate climatic and socioeconomic data into biodiversity policy.

Keywords: ecological corridor, land use, conservation strategy, socioenvironmental pressure, spatial analysis.

1. Introduction

Native vegetation is a cornerstone of ecological integrity, offering benefits that go far beyond biodiversity conservation. It underpins critical ecosystem services such as water filtration (Oldfield *et al.*, 2019), soil stabilization (Fatahi *et al.*, 2015), and pollination (Ferreira *et al.*, 2022), which are essential for both environmental sustainability and human livelihoods. Moreover, native forests and grasslands play a central role in global carbon dynamics, contributing to climate change mitigation through carbon sequestration (Macicasan *et al.*, 2024). These ecosystems also generate economic value by supporting agriculture, forestry, and ecotourism, while simultaneously enhancing social well-being through cultural heritage, recreation, and spiritual connections. Despite their multiple benefits, native vegetation continues to decline globally due to land-use change, agricultural expansion, and infrastructure development (Fischer & Lindenmayer, 2007; Polizel *et al.*, 2021). Its conservation is thus not only an ecological imperative but a foundational element of sustainable land use planning and territorial governance.

The Araguaia Biodiversity Corridor (ABC) represents a strategic ecological and socioenvironmental frontier in Brazil, spanning over 129,000 km² across five states and bridging two of the most threatened yet biologically rich biomes in the world: the Amazon and the Cerrado (**Fig. 1**; Lucchesi *et al.*, 2024). The Corridor was initially identified as one of the strategic connections for the conservation of the jaguar (*Panthera onca*) in Brazil (Silveira et al., 2014). Aligned with the course of the Araguaia River, the corridor extends for approximately 2,800 km, from its headwaters in southwestern Goiás to its confluence with the Amazon River in Pará. This mosaic landscape supports critical ecological functions, including habitat connectivity, climate regulation, and water security, while also housing hundreds of endemic and threatened species. However, ongoing pressures from deforestation, land-use change, and socioeconomic drivers have eroded its ecological functionality (Latrubesse *et al.*, 2009; Coe *et al.*, 2011; Araújo *et al.*, 2021). In this context, the Araguaia Corridor offers a compelling case study to explore how climate and human development intersect to shape conservation outcomes. Understanding the interplay of biophysical and socioeconomic forces across this vast corridor is not only key for regional biodiversity but also essential for advancing land-use policies and ecological restoration strategies.

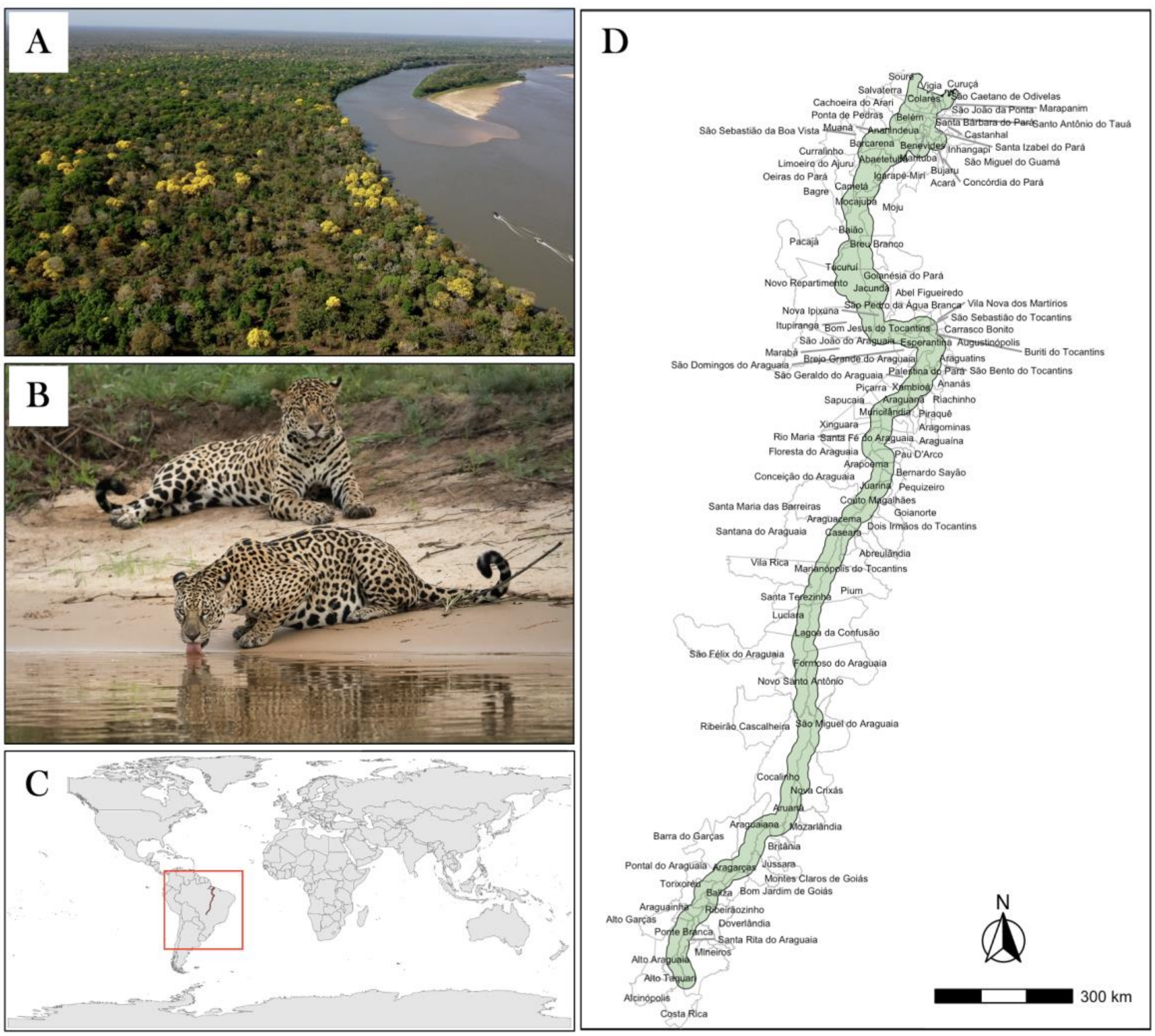

Figure 1. Visual and geographic overview of the Araguaia Biodiversity Corridor (ABC): **A)** view of the Araguaia River and adjacent Cerrado vegetation along its margins; **B)** two jaguars (*Panthera onca*) at the river's edge, one resting and the other drinking water, illustrating the region's ecological richness; **C)** global-scale map showing the location of the ABC in central

Brazil (red box); and **D)** detailed view of the corridor, highlighting the municipalities it intersects. Municipality names are labeled to illustrate the political and administrative diversity along the corridor. The buffer zone includes a 20 km margin on each side of the river channel. Photos in A and B by Leandro Silveira.

While climatic factors have long been recognized as key determinants of vegetation distribution, socioeconomic drivers such as population density, income, and land tenure structure are gaining attention for their role in shaping land use decisions (Dobbs *et al.*, 2017; Knaap *et al.*, 2018; Malek & Verburg, 2020; Jiang *et al.*, 2021). In rapidly transforming frontier landscapes like the ABC (Lucchesi *et al.*, 2024), understanding how these variables interact is important for identifying areas at risk of degradation and for guiding public policy. Yet, few studies have quantified these relationships at the municipal scale or integrated them into practical decision-making tools for land use planning (e.g., García *et al.*, 2017; Martins *et al.*, 2021; Moraes *et al.*, 2023; Lima-Júnior *et al.*, 2024; Lucchesi *et al.*, 2024). This gap limits our ability to balance conservation goals with the socioeconomic needs of local populations.

Reconciling biodiversity conservation with economic development presents significant challenges in the corridor. Municipalities vary widely in terms of infrastructure, agricultural productivity, and demographic dynamics, which often lead to contrasting land use pressures (Schwaab *et al.*, 2017; Meyer *et al.*, 2021; Timilsina *et al.*, 2025). In some areas, high deforestation rates are closely tied to commodity-driven agriculture, while in others, low vegetation cover reflects rapid urban expansion or weak environmental enforcement. Effective land use policy requires not only identifying the underlying drivers of vegetation loss but also understanding where and why certain areas diverge from expected ecological patterns. Bridging this knowledge gap is essential to designing interventions that are both equitable and ecologically sound. Recent projections highlight the tangible value of such efforts. According to Lucchesi and colleagues (2024), the full restoration of the ABC over the next 50 years could generate net societal benefits of US$ 19.8 billion under an ecological pathway and US$ 18.9 billion under an economic pathway, with positive outcomes across all macro-regions and rural property sizes. These estimates underscore the urgency and feasibility of integrating conservation with sustainable development at scale.

Our study addresses these challenges by analyzing how climatic, economic, and demographic variables influence native vegetation cover across 108 municipalities intersecting the ABC. Using a linear modeling framework, we quantify the role of annual precipitation, Gross Domestic Product (GDP), population density, and rural land structure in shaping vegetation patterns. Beyond identifying these drivers, we introduce a novel Socioenvironmental Pressure Index (SPI) that measures the extent to which each municipality deviates from expected vegetation levels based on its socio-climatic context. This index allows for the spatial identification of priority areas for conservation or restoration efforts. By integrating environmental and socioeconomic data into a spatially explicit framework, we contribute to the growing literature on evidence-based land use planning. Our results also align with current legislative initiatives to formalize ecological corridors in Brazil, including the proposed federal bill PL 909/2024, which aims to legally establish the ABC, and the National Biodiversity Policy (Decree No. 4.339/2002), which recognizes ecological corridors as strategic instruments for maintaining ecosystem connectivity and functionality. These findings highlight the need for adaptive, place-based policies that account for both ecological and human dimensions of landscape change. Understanding the interplay of biophysical and socioeconomic forces across this vast corridor is not only key for regional biodiversity but also essential for advancing land-use policies, protecting the generation of environmental services, and advancing ecological restoration strategies.

2. Material and methods

2.1. Data source

To investigate the socioenvironmental dynamics within the Araguaia Biodiversity Corridor (ABC), we first defined the corridor as a 40-kilometer-wide ecological strip along the Araguaia River, consisting of a 20 km buffer on each side of the river channel. This buffer-based approach follows similar strategies used in the delineation of ecological corridors in Brazil (e.g., MMA, 2002; Ribeiro *et al.*, 2009; Lucchesi *et al.*, 2024)) and reflects both the zone of ecological influence of the river and the area targeted by current legislative initiatives (PL 909/2024). The geographic extent of the ABC thus includes all 125 municipalities that intersect this 40 km corridor (**Fig. 1**). The selected variables represent commonly used indicators of socioeconomic development, land use, and climatic conditions in environmental and landscape ecology studies (e.g., Dobbs *et al.*, 2017; Malek & Verburg, 2020; Moraes *et al.*, 2023), allowing for an integrated assessment of their potential influence on native vegetation cover. Socioeconomic variables included the Human Development Index (HDI), obtained from the Brazilian Institute of Geography and Statistics (PNUD *et al.*, 2013), which integrates indicators of education, income, and life expectancy; population density, also provided by IBGE (2022), which reflects demographic pressure on land and resources; and Gross Domestic Product (GDP), as a proxy for economic activity at the municipal level (IBGE, 2021).

Climatic data were derived from the global dataset developed by Fick & Hijmans (2017), providing high-resolution (approximately 1 km^2) estimates of mean annual precipitation and temperature (temporal range of 1970–2000). These variables are critical for understanding the environmental gradients influencing vegetation distribution and ecological processes across the corridor. Property structures were assessed using data from the National Rural Registration System, maintained by the National Institute for Colonization and Agrarian Reform (INCRA, 2024). This dataset provides detailed information on the number of registered rural properties and their size (km^2) in each municipality, enabling the evaluation of land ownership patterns and their potential role in shaping land use intensity. Finally, native vegetation, soybean cultivation, and pasture areas were derived from the Land Use and Land Cover Map (Collection 9) of MapBiomas (MapBiomas, 2024), which offers annual, high-resolution (approximately 1 km^2) satellite-based classifications of land cover across Brazil. The dataset is produced by a collaborative network of research institutions, universities, and NGOs, providing consistent and spatially detailed information to support land use and environmental analyses.

2.2. Statistical analyses

To ensure analytical relevance, we excluded municipalities with less than 5% of their territory intersecting the corridor, yielding a final sample of 108 municipalities. Prior to modeling, all continuous variables were evaluated for skewness, and appropriate transformations were applied to improve data normality. Logarithmic transformations were used for the number of rural properties, native vegetation area, GDP, and population density, while a square root transformation was applied to mean property size, soybean cultivation area, and pasture areas which proved more effective in reducing its skewness. All analyses were performed in RStudio (R Core Team, 2024). Full data and code can be found in the Supplementary Material as Table S1.

We used linear regression models to identify the key drivers of native vegetation cover. The initial model included all candidate predictors in an additive framework (Table S2). Model selection was performed using the dredge function from the MuMIn package (v. 1.48.4; Bartoń, 2024), which ranked models based on Akaike Information Criterion corrected for small samples (AICc). Twelve models were considered plausible ($\Delta AICc < 2$), and we selected the most parsimonious among them (the model with fewer parameters) for interpretation. The final model excluded HDI, mean annual temperature, soybean cultivation area, and pasture area, as their inclusion did not enhance model performance or substantially reduce information criteria values (Table S2). An alternative model including interaction terms between best predictors was also tested but showed inferior fit ($AICc > 2$) compared to the additive model. We also assessed whether residuals from the selected model exhibited spatial autocorrelation using Moran's I test. Spatial neighborhoods were defined using queen contiguity among municipalities. The resulting test was non-significant (Moran's $I = -0.025$, $p = 0.59$), indicating no detectable spatial structure in the residuals. Therefore, we retained the linear model without additional spatial correction and report coefficient significance accordingly.

2.3. Socioenvironmental Pressure Index

To identify municipalities where vegetation cover deviates from what would be expected based on socio-climatic conditions, we developed a Socioenvironmental Pressure Index (SPI). The index is grounded in the residuals of the final linear model, which captures the discrepancy between observed and predicted values of native vegetation cover, after accounting for climatic (precipitation), economic (GDP), demographic (population density), and land structure variables (number and size of rural properties). The underlying rationale is that municipalities with significantly less vegetation than predicted by these drivers are likely subject to additional pressures (such as unregulated land use, weak enforcement, or historical degradation) not captured by the model covariates. To compute the SPI, we inverted the model residuals (multiplying by −1) so that higher values correspond to greater pressure. These values were then standardized (z-scores) to facilitate comparison across municipalities. Positive SPI scores indicate areas with lower-than-expected vegetation cover, suggesting heightened socioenvironmental pressure. Negative scores, conversely, identify municipalities with more vegetation than predicted, which may signal resilience, effective land governance, or lower human impact. This approach allows for the spatial prioritization of conservation interventions by highlighting where vegetation loss exceeds model-based expectations.

3. Results

3.1. Land use patterns

The analysis of land use proportions across the 108 municipalities intersecting the Araguaia Biodiversity Corridor reveals substantial spatial variability **(Fig. 2)**. On average, 55.3% of the municipal territory is located within the corridor boundaries, but this varies from 5.9% to 100% **(Fig. 2A)**. Some municipalities, such as Belém (PA) and Aragarças (GO), are entirely encompassed by the corridor, while others like Marianópolis do Tocantins (TO) and Bagre (PA) are only marginally included. This heterogeneity reflects differing conservation potentials and land use pressures. The native vegetation cover average is 46.5% of municipal land, ranging from 10.4% to 93.5% **(Fig. 2B)**. Municipalities such as Novo Santo Antônio (MT), Lagoa da Confusão (TO), and Soure (PA) maintain particularly high native vegetation levels—above 85%—highlighting their importance for biodiversity conservation. Conversely, places like Buriti do Tocantins (TO) and Piçarra (PA) show severe land conversion, with native vegetation comprising less than 15% of their territory.

Pasture areas account for 43.4% of municipal land on average, with a wide range from nearly 0% to 88% **(Fig. 2C)**. High values are observed in municipalities such as Bernado Sayão (TO) and São Domingos do Araguaia (PA), indicating regions with intense livestock activity. In contrast, municipalities like Ponta de Pedras (PA) and Limoeiro do Ajuru (PA) report very low pasture coverage — under 1% — suggesting reduced grazing pressure or dominance of other land uses. Soy cultivation is spatially concentrated but reaches extreme values in select areas **(Fig. 2D)**. Although the average across the corridor is just 2.5%, municipalities such as Alto Taquari (MT) register soy plantations covering more than 40% of their municipal territory, reflecting zones of industrial-scale agriculture. Meanwhile, more than half of the municipalities—especially those located in Pará and Tocantins—report negligible soy production.

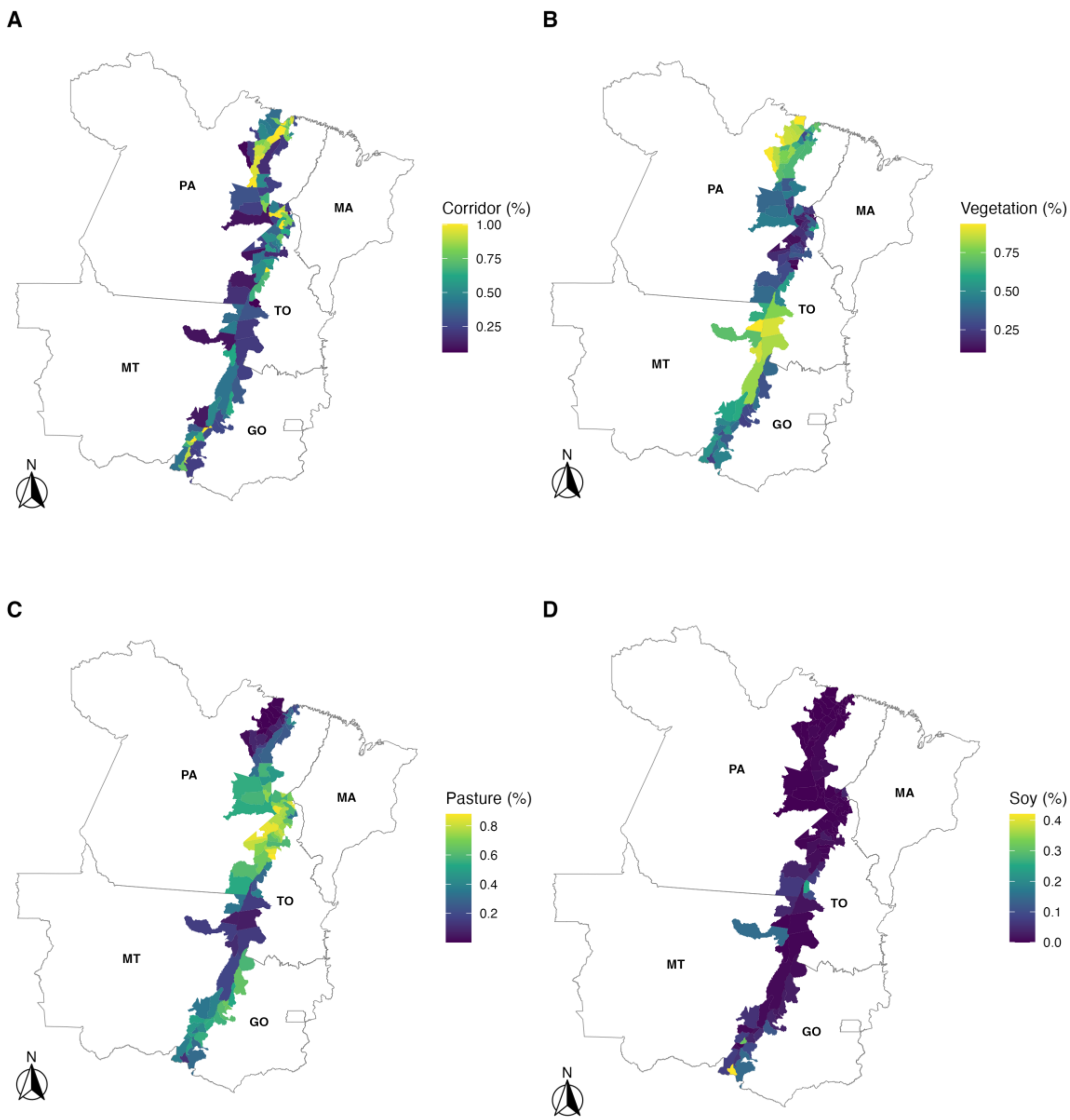

Figure 2. Spatial distribution of land use proportions across municipalities within the Araguaia Biodiversity Corridor: **A)** proportion of municipal territory that overlaps with the corridor; **B)** proportion of native vegetation cover; **C)** proportion of pasture area; and **D)** proportion of soy plantation. All values represent the percentage of each land use class relative to the total area of each municipality, allowing comparison across different-sized territories.

3.2. Climatic conditions

Climate across the Araguaia Biodiversity Corridor varies considerably from one region to another, reflecting the corridor's complex environmental gradients (**Fig. 3**). The mean annual temperature across municipalities is 25.76°C, ranging from 21.7°C in cooler southern regions like Alto Taquari (MT) and Mineiros (GO) to peaks above 27°C in municipalities such as Soure (PA) and Salvaterra (PA) (**Fig. 3A**). Temperature variability, as measured by standard deviation, ranges from 0.04°C in Inhangapi (PA)—indicating an exceptionally stable thermal environment—to nearly 0.87°C in more climatically variable municipalities like Barra do Garças (MT).

The average annual precipitation within the corridor is 165.3 mm, though marked disparities among municipalities highlight the region's diverse hydroclimatic regimes (**Fig. 3B**). The driest regions, such as Augustinópolis (TO) and Aragarças (GO), receive less than 130 mm annually. In contrast, northern municipalities like Soure (PA) and Salvaterra (PA) experience precipitation levels exceeding 245 mm, representing the wetter end of the climatic spectrum. The standard deviation of annual precipitation, used as a proxy for rainfall variability, also varies widely—from as low as 1.05 mm in Aragarças (GO) to over 16.4 mm in Cachoeira do Arari (PA), highlighting areas with highly unstable rainfall regimes.

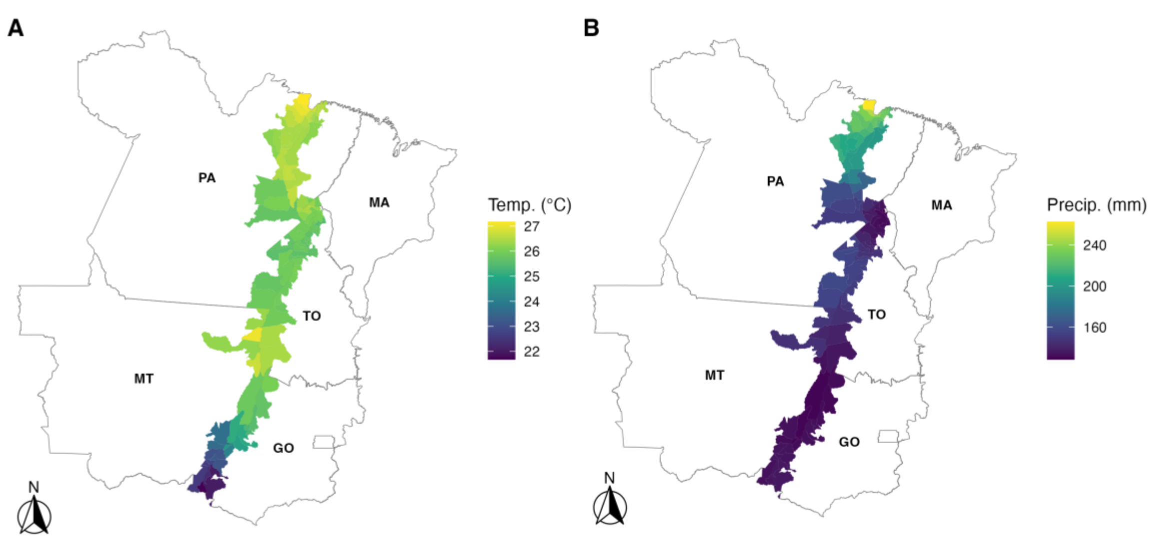

Figure 3. Climatic patterns across municipalities intersecting the Araguaia Biodiversity Corridor: **A)** mean annual temperature (°C); and **B)** mean annual precipitation (mm). Values are aggregated at the municipal level and represent long-term climatic averages. Colder and

dryer municipalities are generally concentrated in the southern and central-southern regions, respectively.

3.3. Socioeconomic scenario

The 108 municipalities intersecting the Araguaia Biodiversity Corridor display substantial socioeconomic diversity, as revealed by metrics such as the Human Development Index (HDI), Gross Domestic Product (GDP), population density, number of rural properties, and average rural property size **(Fig. 4)**. The HDI averages 0.625, with values ranging from 0.471 in Bagre (PA)—indicating low levels of education, income, and longevity—to 0.752 in Araguaína (TO), one of the most socioeconomically developed municipalities in the corridor. Most municipalities fall within the "medium" development category, though a clear spatial gradient exists, with generally higher IDHM values in the southern portion of the corridor **(Fig. 4A)**. The municipal GDP exhibits extreme variation, with an average of R$ 1.2 million, but highly skewed by a few wealthy municipalities **(Fig. 4B)**. For example, Belém (PA) stands out with a GDP exceeding R$ 33 million, driven by its industrial and port activities, while smaller rural municipalities such as Araguainha (MT) report values below R$ 30,000, highlighting stark economic contrasts across the corridor.

Population density follows a similar pattern of heterogeneity **(Fig. 4C)**. While the average is 63.1 inhabitants/km^2, over half the municipalities exhibit densities below 10 inhabitants/km^2, particularly in interior regions such as Cocalinho (MT) and Pium (TO). In contrast, Ananindeua (PA) reaches a density of over 2,500 inhabitants/km^2, reflecting urbanization and infrastructure concentration. Regarding the structure of land occupation, the number of rural properties per municipality ranges from just 56 in Marituba (PA) to more than 4,300 in Moju (PA), with a mean of 1,094 properties **(Fig. 4D)**. Meanwhile, the average size of rural properties is 133.95 km^2, but this also varies widely—from just 20 km^2 in municipalities like Barcarena (PA) to over 350 km^2 in Araguaína (MT), reflecting different models of land use and tenure **(Fig. 4E)**.

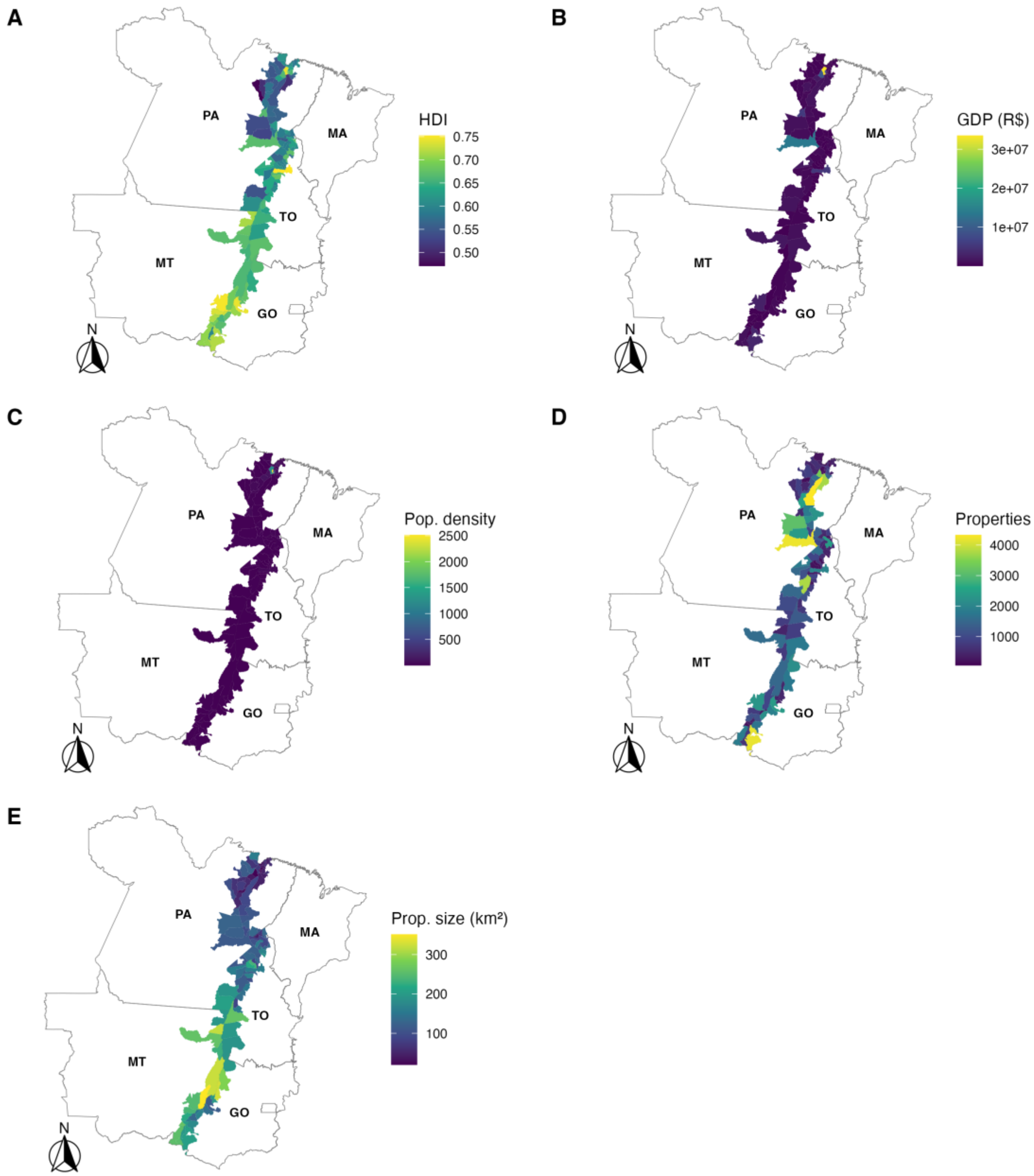

Figure 4. Socioeconomic variation across the 108 municipalities intersecting the Araguaia Biodiversity Corridor: **A)** Human Development Index (HDI), with most municipalities falling into the medium development category and higher values concentrated in the southern portion of the corridor; **B)** Gross Domestic Product (GDP in BRL), showing strong disparities, from industrial urban centers to small rural municipalities; **C)** population density (inhabitants/km²), with highly urbanized areas contrasting with sparsely populated interior regions; **D)** number of registered rural properties per municipality; and **E)** average size of

rural properties (km²), reflecting distinct land tenure structures. All values are aggregated at the municipal level and illustrate the corridor's socioeconomic heterogeneity.

3.4. Drivers of vegetation cover

The results of the final model demonstrate a high level of explanatory power for predicting native vegetation area (log-transformed) based on selected climatic, socioeconomic, and demographic variables, with an R^2 of 0.85, indicating that approximately 85% of the variation in native vegetation cover is explained by the predictors (**Fig. 5**; **Table 1**; see Supplementary Material for further statistics). The model's overall significance ($p < 0.001$) confirms its robustness and adequacy. Among the predictors, mean annual precipitation showed a positive and highly significant effect on native vegetation ($\beta = 0.0229$; $p < 0.001$; 95% CI: 0.02 to 0.03), suggesting that wetter areas tend to support broader vegetation cover—consistent with the role of favorable climatic conditions in sustaining natural ecosystems. In contrast, population density exhibited a strong negative effect ($\beta = -0.7348$; $p < 0.001$; 95% CI: -0.91 to -0.56), indicating that more densely populated municipalities tend to have reduced native vegetation cover, likely due to urbanization, infrastructure development, and other anthropogenic pressures. Interestingly, GDP showed a positive association with vegetation cover ($\beta = 0.5055$; $p < 0.001$; 95% CI: 0.36 to 0.65), suggesting that more prosperous municipalities, possibly with greater access to conservation resources and environmental governance, tend to preserve larger areas of native vegetation. Additionally, both the number of rural properties ($\beta = 0.4064$; $p = 0.001$; 95% CI: 0.21 to 0.60) and the average property size ($\beta = 0.1150$; $p < 0.01$; 95% CI: 0.05 to 0.18) were positively correlated with vegetation cover. This may reflect the influence of legal frameworks or land-use regulations in areas with higher land parcelization, as well as the lower land-use intensity often associated with larger properties. Overall, these findings highlight the integrated role of climatic, economic, and demographic factors in shaping patterns of native vegetation across the Araguaia Biodiversity Corridor.

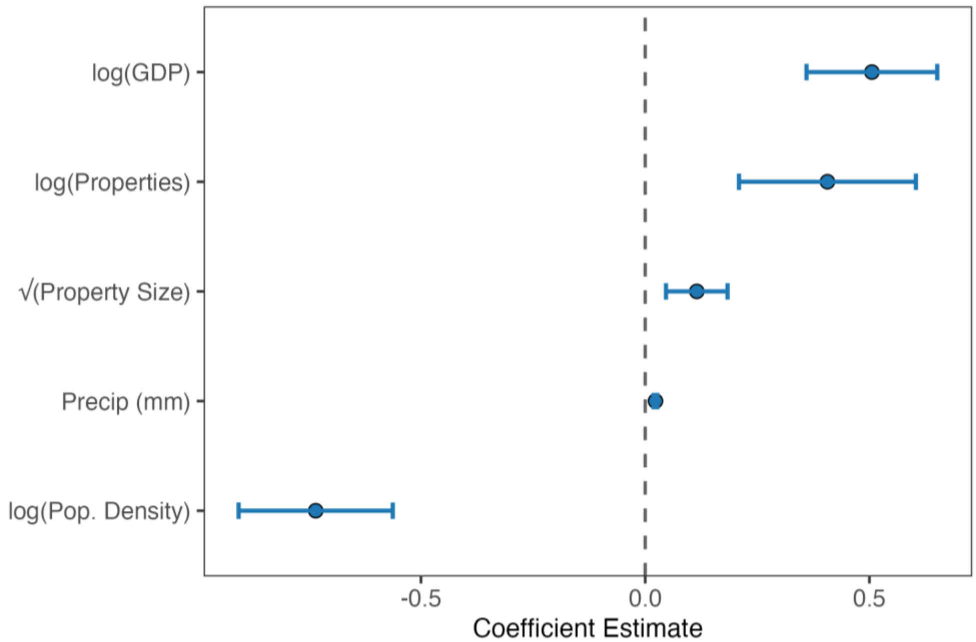

Figure 5. Regression coefficients and confidence intervals of the best linear model predicting native vegetation cover in response to explanatory variables across municipalities intersecting the Araguaia Biodiversity Corridor.

Table 1. Additive linear model testing whether native vegetation cover is explained by the socioenvironmental variables of municipalities within the Araguaia Biodiversity Corridor.

Response	Predictor	Estimate	SD	t-value	p-value	R^2	AICc	AICc (Null Model)
Native vegetation area (log)	Intercept	-6.030	0.794	-7.592	< 0.001	0.852	185.3	380.5
	Mean annual precipitation	0.023	0.002	11.311	< 0.001			
	Population density (log)	-0.735	0.087	-8.480	< 0.001			
	GDP (log)	0.506	0.074	6.877	< 0.001			
	Number of rural properties (log)	0.406	0.099	4.087	< 0.001			
	Average property size (sqrt)	0.115	0.035	3.322	0.001			

To synthesize the influence of climate, economic activity, and demographic patterns on native vegetation cover, we developed a Socioenvironmental Pressure Index (SPI) based on the residuals of the final regression model. Residuals capture the discrepancy between observed and predicted native vegetation values, after controlling for key predictors. Municipalities with large negative residuals exhibit less vegetation than expected, indicating greater socioenvironmental pressure. Conversely, positive residuals suggest that vegetation cover is higher than predicted, possibly due to effective land management, conservation efforts, or lower human pressure than reflected in the model. This index serves as a diagnostic tool to identify priority areas for intervention, where vegetation loss exceeds what would be anticipated given the climatic and socioeconomic context. It complements spatial policy instruments and can support adaptive land-use planning and restoration efforts throughout the corridor (**Fig. 6**).

Municipalities such as Arapoema (TO), Bernado Sayão (TO), Barcarena (PA), and Alto Taquari (MT) displayed some of the highest SPI values (> 2), meaning their observed native vegetation cover is significantly lower than what would be expected based on their climate, GDP, population density, and rural property structure. These areas may be experiencing intensified deforestation pressures or land-use conflicts not captured directly by the model's predictors and, thus, should be considered priority zones for ecological restoration, land regularization programs, or improved enforcement of environmental regulations.

On the other hand, municipalities like São Bento do Tocantins (TO), Cametá (PA), and Aragarças (GO) exhibited lowest SPI values (< -2), indicating they maintain more native vegetation than expected. These cases may reflect successful conservation policies, lower economic or demographic pressure, or traditional land-use practices that contribute to vegetation retention. Understanding the conditions behind these positive outliers can help inform best practices for replication across the corridor, especially in regions facing increasing socioenvironmental pressures.

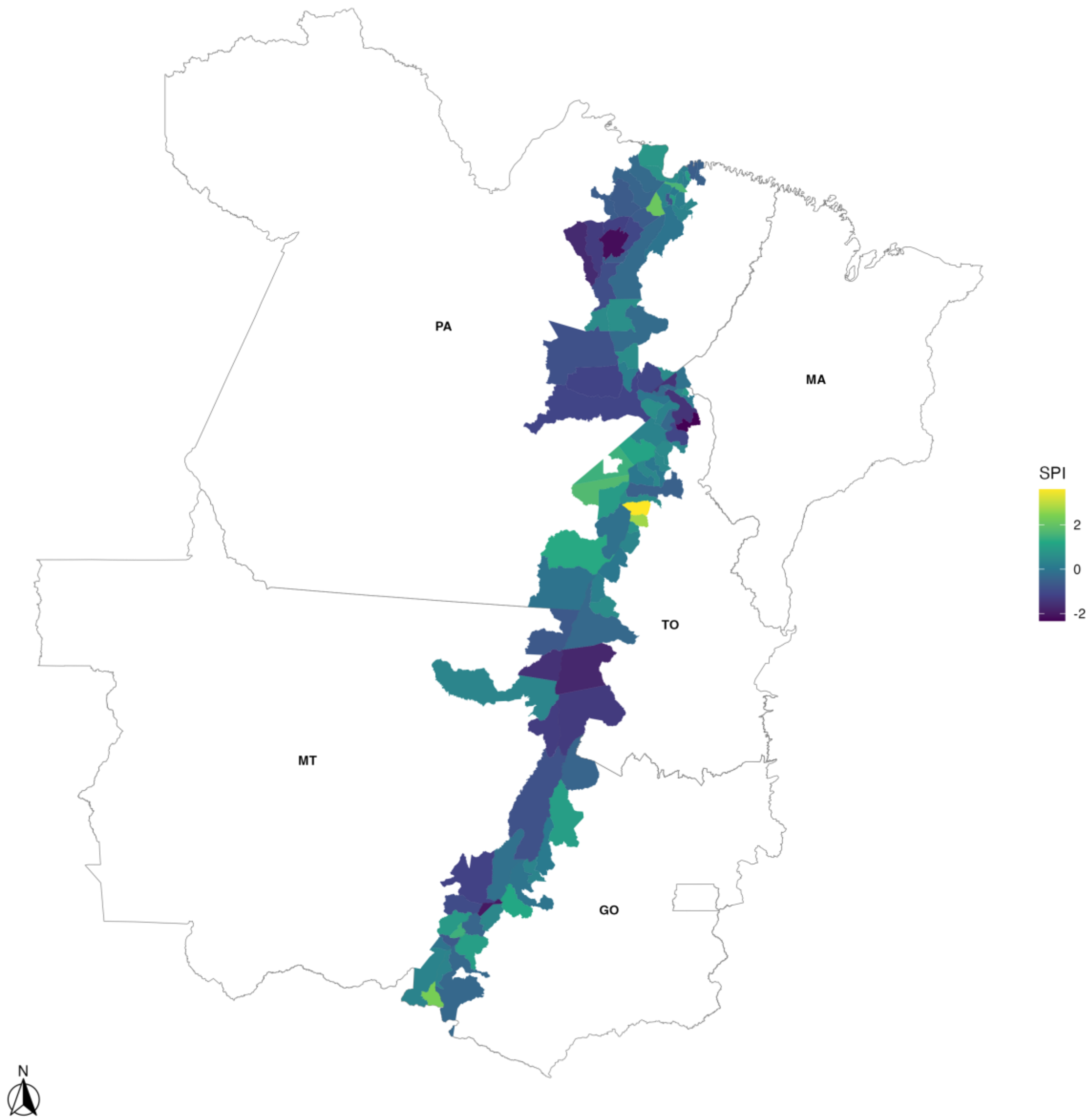

Figure 6. Socioenvironmental Pressure Index (SPI) across municipalities in the Araguaia Biodiversity Corridor. Lighter shades indicate higher SPI values, reflecting greater socioenvironmental pressure and less native vegetation than expected; darker shades denote lower SPI values, suggesting more vegetation cover than predicted.

4. Discussion

The findings of this study highlight the complex and spatially heterogeneous socioenvironmental dynamics shaping the Araguaia Biodiversity Corridor (ABC). Native vegetation cover varies considerably across municipalities, reflecting stark differences in land use intensity, degree of corridor integration, and ecological pressure. While some municipalities retain high vegetation levels and substantial territorial overlap with the corridor, acting as biodiversity strongholds, others show extensive land conversion due to pasture and soy expansion, underscoring the need for spatially tailored conservation strategies. Climatic gradients further influence vegetation patterns, with precipitation emerging as a key positive driver, while mean annual temperature shows no significant effect, likely due to limited variation across the study area. This suggests that water availability plays a more decisive role than thermal conditions in supporting ecosystem structure and resilience across the corridor (Margulis & Unterstell, 2016; Rattis *et al.*, 2021).

In parallel, socioeconomic indicators reveal a mosaic of urban, peri-urban, and rural realities, with considerable variation in GDP, population density, and land tenure structure. These differences shape not only land use practices but also the capacity of municipalities to enforce environmental regulations and engage with conservation programs. Importantly, these patterns reflect broader trends observed in other tropical and subtropical landscapes, where conservation outcomes are not solely determined by biophysical constraints but are also strongly influenced by governance capacity, historical land use, and developmental trajectories (Sparovek *et al.*, 2015; Huang *et al.*, 2018; Alfred *et al.*, 2021; Ayambire *et al.*, 2025). Taken together, these findings emphasize the need for conservation policies that are adaptive to local conditions, integrating environmental, social, and economic dimensions to effectively balance biodiversity protection with sustainable development across frontier regions like the ABC.

The final regression model revealed clear and consistent relationships between native vegetation cover and key climatic, demographic, and economic variables. Particularly notable is the dual role of socioeconomic indicators. GDP showed a positive association with vegetation cover, suggesting that wealthier regions may possess greater capacity for environmental governance, investment in sustainable land management, or effective enforcement of conservation regulations. This pattern challenges the traditional narrative that economic growth invariably leads to environmental degradation (Alvarado & Toledo, 2017). However, similar findings have been reported in other rapidly developing regions, such as the Pearl River Delta in China, where Hu and Xia (2019) demonstrated that increased GDP correlated strongly with gains in vegetation cover, driven by urban greening programs, afforestation policies, and ecological compensation mechanisms. These dynamics may also be playing out in the ABC, where more affluent municipalities, potentially equipped with better infrastructure, environmental agencies, and political leverage, are not only capable of maintaining native vegetation but may also lead in restoration and conservation innovation. This reinforces the notion that when guided by sustainability-oriented policies and investments, economic prosperity can align with ecological integrity, offering a "win-win" scenario for biodiversity and development.

In contrast, human population density emerged as a significant negative predictor of native vegetation cover, indicating that more densely populated municipalities tend to experience greater environmental pressure. This finding is consistent with global and regional studies that associate demographic concentration with land conversion, infrastructure expansion, and increased demand for agricultural space (Luck *et al.*, 2009; Wellmann *et al.* 202). While GDP may reflect a municipality's economic capacity to invest in environmental protection, population density often correlates with urban sprawl, informal settlements, and fragmented governance, all of which can accelerate habitat loss when not managed through robust planning frameworks (Liu *et al.*, 2016). In the context of the ABC, high-density municipalities may face greater challenges in balancing human needs with conservation goals, particularly where land tenure is contested, or environmental regulations are poorly enforced. These contrasting effects of economic and demographic indicators reinforce the need for integrated, multi-scalar conservation policies that address not only the availability of resources but also the spatial intensity of land use and the institutional capacity to manage it effectively.

The positive association between native vegetation cover and both the number and average size of rural properties in our model suggests that landholding structure is important in shaping conservation outcomes. This relationship likely reflects multiple mechanisms. On one hand, municipalities with many rural properties may exhibit higher overall compliance with legal reserve requirements due to increased land fragmentation and regulatory oversight.

On the other hand, larger properties may be more compliant with environmental regulations and retain more vegetation, not only due to better access to technical resources, credit, and enforcement mechanisms, but also because legal reserve requirements scale proportionally with property size. In the Brazilian Cerrado, for example, larger properties (>1,000 ha) have significantly higher compliance with the Forest Code and harbor most of the remaining native vegetation, accounting for 93% of surplus forest beyond legal reserve requirements (Stefanes et al., 2018). In our study, such patterns align with a broader understanding that structural and economic factors, as land tenure, property size, and governance, shape the effectiveness of conservation policy implementation. Recognizing this, land use strategies and restoration incentives should consider property structure explicitly, especially in regions where larger landholders may offer significant opportunities for preserving ecological integrity at scale.

Among the tested climatic variables, mean annual precipitation emerged as a positive predictor, indicating that wetter municipalities tend to sustain more extensive native vegetation. This relationship reflects the ecological importance of water availability in supporting primary productivity, maintaining soil moisture, and enabling the persistence of moisture-dependent ecosystems, particularly in ecotonal regions where Amazon and Cerrado biomes overlap (Latrubesse *et al.*, 2019; Yang *et al.*, 2025). In contrast, mean annual temperature showed no significant association with vegetation cover in the final model. This may be due to the relatively narrow range of temperature variation across the corridor compared to precipitation gradients, or because vegetation in the region is already adapted to tropical thermal regimes. Thus, our findings underscore the primacy of water-related factors over thermal ones in explaining vegetation patterns at the landscape scale in tropical and subtropical transitional zones such as the ABC.

Building on these contrasting dynamics, the Socioenvironmental Pressure Index (SPI) serves as a spatial diagnostic tool to identify municipalities where native vegetation cover significantly diverges from expectations based on climatic and socioeconomic conditions. By capturing the residual variation from the final model, the SPI reveals hidden dynamics of degradation or resilience. Municipalities with high SPI values, those with less vegetation than predicted, represent pressure hotspots likely affected by unmeasured stressors such as illegal deforestation, informal land use, or weak governance. These areas often align with high population density and institutional fragility. In contrast, low SPI values highlight municipalities that maintain more vegetation than expected, suggesting the influence of local stewardship, effective policy implementation, or traditional land practices. The SPI thus enhances conventional indicators by uncovering spatially specific vulnerabilities and successes, supporting targeted conservation and restoration efforts across the corridor.

From a policy perspective, these findings are timely and directly relevant to the implementation of PL 909/2024, which seeks to formalize the ABC in Brazilian law. The bill emphasizes ecological connectivity, sustainable land use, and inclusive territorial governance, all of which resonate with our empirical evidence. The corridor's municipalities vary not only in their biophysical contexts but also in their capacity to engage with conservation agendas. Policies that fail to recognize this diversity risk being ineffective or even counterproductive. Therefore, tailored approaches that consider each municipality's environmental condition, economic structure, and institutional strength will be essential for the corridor's long-term success.

This study contributes to a growing body of evidence supporting conservation models that integrate social, economic, and climatic variables at landscape scales (e.g. Sanderson *et al.*, 2002; Price *et* al., 2012; Lacher *et al.* 2023). The ABC, given its ecological and geopolitical relevance, can serve as a testbed for operationalizing such integrated approaches. Tools like the SPI, when combined with high-resolution spatial data and participatory planning, can inform adaptive management strategies that are both scientifically grounded and socially equitable. In doing so, Brazil can not only advance its biodiversity commitments under national and international frameworks but also demonstrate how science-based territorial governance can reconcile development and conservation in frontier regions.

Acknowledgements

This work is supported by the "Araguaia Vivo", in the context of an agreement between the Tropical Water Research Alliance (TWRA) and FAPEG (proc. 202210267000536), and by the "PPBio Araguaia" project supported by CNPq (proc. 441114/2023-7). Work by MAME and JAFDF in geographical analyses of the Araguaia River corridor has also been developed under the National Institute of Science and Technology (INCT) in Ecology, Evolution, and Biodiversity Conservation, funded by CNPq (grant 465610/2014-5) and FAPEG (grant 201810267000023). JAFDF has been continuously supported by productivity grants from CNPq. We also acknowledge Oreades Núcleo de Geoprocessamento for their institutional support, particularly in the elaboration, production, and donation of geospatial data that have contributed to the development of this research.

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6. Supplementary Material

Table S1: Full dataset used in the study.

https://drive.google.com/drive/folders/1ZkAA6_UuP_mQfGrfoqw7Ckj03uWgKXwA?usp=sharing.

Table S2: Model selection outputs.

https://drive.google.com/file/d/1vgxN50PmdmdBYOJChScXWCr2MEGLl-p1/view?usp=drive_link.

Code: Script for analyses in R.

https://drive.google.com/file/d/1YHBlQESRBLpUeuGPG3QzhWGq323VZbtF/view?usp=drive_link.