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Papers

Deforestation in Areas of Higher Suitability Does Not Imply Greater Productivity: The Mismatch Between Environmental and Economic Sustainability in the Cerrado

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Abstract

The expansion of agriculture in the Cerrado has led to the highest deforestation rates in Brazil. The conversion of these areas is not only linked to biodiversity loss and the decline of ecosystem services but also does not result in increased agricultural productivity. Considering the Matopiba region— zone of the Cerrado with the highest deforestation rate in the biome—maintaining the current deforestation rate in areas of highest agricultural productivity will lead to the disappearance of native vegetation within the next decade. This land-use conversion is not driven by economic potential, as the most suitable areas for agriculture are predominantly occupied by livestock farming, a less profitable activity, indicating allocative inefficiency. Of the total 18.17 Mha already in use within lands suitable for agriculture, 12.75 Mha are occupied by livestock farmings, with no substantial economic contribution from livestock.

Given the need to maintain agricultural productivity in the face of constant market demand, it is essential to establish environmental policies that promote both economic and environmental sustainability. To ensure sustainable growth, environmental policies should leverage land suitabilitys data to boost productivity, direct agricultural financing, and enforce stricter land-use rules—shifting crop expansion from native vegetation to livestock farming conversion in high-suitability areas.

Additionally, to prevent the complete elimination of the Cerrado in these areas, it is crucial to establish a higher proportion of legal reserves as a condition for granting new land-clearing licenses. Here, we suggest 60% for areas of highest agricultural suitability, compared to the 20% required by the current Forest Code (Federal Law No. 12,651 of May 25, 2012), aiming to double the lifespan of remaining native vegetation. The measures proposed here outline a pathway for maintaining and increasing the country's agricultural productivity sustainably, mitigating the major impacts of land-use change on biodiversity and ecosystem services.

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INTRODUCTION

The Brazilian Cerrado is the country's second-largest biome, covering nearly a quarter of its territory—198.5 Mha (MapBiomas, 2024). Although dominated by deep, highly leached soils with low natural fertility and high exchangeable aluminum content (Oliveira *et al.*, 2023), it contrasts as the nation's largest agricultural frontier (Rada, 2013) and a vital provider of regulating, provisioning, and cultural ecosystem services (Giroldo; Scariot, 2015; Schmidt *et al.*, 2007; Nóbrega *et al.*, 2020; Chiaravalloti *et al.*, 2022).

The Cerrado's vast distribution fosters unique environmental heterogeneity, with vegetation diversity and structure shaped by edaphic and climatic factors (Ratter *et al.*, 2003; Bueno *et al.*, 2018). It harbors one-third of Brazil's vascular plant species (Flora e Funga do Brasil, 2024) and half of its birds, reptiles, and fish (Klink; Machado, 2005). Its high biodiversity, endemism, and escalating deforestation threat classify it as a global conservation priority hotspot (Myers *et al.*, 2000).

The advent of mechanized agriculture, driven by Plano Nacional de Desenvolvimento (National Development Plans – PND) in the 1960s–1970s, colonization projects, and the Programa de Cooperação. Nipo-Brasileiro para o Desenvolvimento Agrícola dos Cerrados (Japan-Brazil Cooperation Program for Cerrados Agricultural Development – PRODECER), spurred profound demographic, urban, and productive shifts in the region (Pessôa; Inocêncio, 2014; Rodrigues *et al.* 2009). This transformation solidified large-scale modern agriculture, positioning Brazil as a leading global producer and exporter of agricultural commodities (Dutra; Souza, 2017; Marques; Lima, 2023). By 1985, 30% of the biome's original cover (59.5 Mha) had already been converted to farmland (MapBiomas, 2024). Land-use conversion persisted at high rates, and by 2023, half of the Cerrado's native vegetation had been lost, leaving only 101 Mha intact (MapBiomas, 2024). Currently, the highest deforestation rates occur in Matopiba—a region spanning Maranhão, Tocantins, Piauí, and Bahia, which holds 30% of the Cerrado's area and remains its most preserved portion despite rapid clearing (MapBiomas, 2024).

Rising global demand for agricultural commodities and financial globalization directly influence deforestation and ecological degradation, though technological innovation and effective environmental policies may mitigate these impacts (Carreira *et al.*, 2024; Ly, 2025). To optimize land use, the Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Corporation - Embrapa) developed an agricultural suitability assessment system for Matopiba (Lumbreras *et al.*, 2015), balancing technical and economic efficiency. This system evaluates soil nutrient supply, water retention, mechanization suitability, and erosion susceptibility, designating unsuitable areas for conservation (Ramalho-Filho; Beek, 1995). Notably, native vegetation clearance in the Cerrado is regulated by the Forest Code, which mandates that 20% of rural properties be preserved as Legal Reserves—a stark contrast to the 80% required in the Amazon. Yet, Matopiba faces rampant illegal deforestation, resulting in fines and land embargoes (IBAMA, 2024).

Sustainable agricultural growth must prioritize productivity gains through land-use efficiency and technology rather than resource overexploitation (Rada, 2013). Thus, this study analyzes land-use patterns and deforestation rates in Matopiba, focusing on varying agricultural suitability classes.

METHODOLOGICAL FRAMEWORK AND ANALYSIS CRITERIA

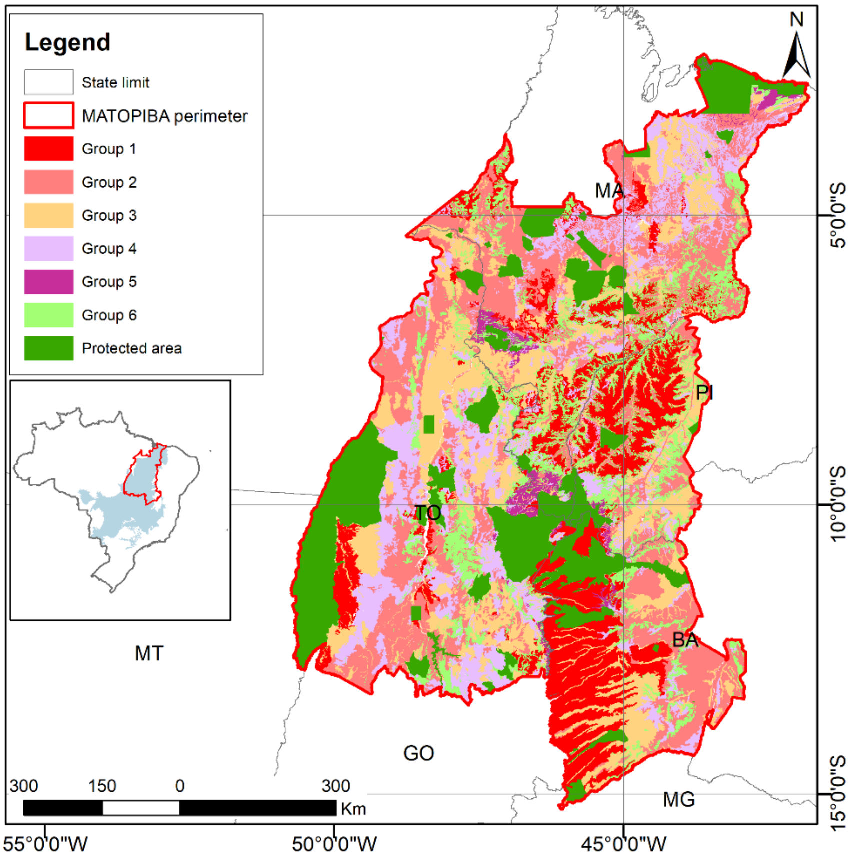
The Matopiba region is politically defined by the dynamics of modern agricultural expansion and its economic growth observed in recent decades (Bezerra; Gonzaga 2019; Miranda *et al.*, 2014; Souza; Pereira 2019). It comprises approximately 73 Mha, of which 91% is associated with the Cerrado biome, 1.7% with the Caatinga biome, and 7.3% with the Amazon biome (Embrapa, 2025). The climate is predominantly Aw (tropical seasonal dry, according to Köppen's classification), with temperatures above 18°C in all months of the year (averaging between 23 and 29°C) and precipitation varying seasonally and spatially (averaging 800 mm.year^{-1} in the portion bordering the Caatinga and 2000 mm.year^{-1} in the area bordering the Amazon) (Lumbreras *et al.*, 2015).

The area shows a predominance of Oxisols (31.1%), Ultisols (12.8%), Petroplinthic Plinthosols (8.7%), Arenosols (8.7%), and Leptosols (7.2%). Naturally more fertile soils, such as Luvisols, Nitisols, Vertisols, and Chernozems, are rare and collectively represent less than 2% of the area. Poorly drained lowlands contain Plinthosols (3.9%), Gleisoil's

(1%), and Planosoils (0.9%) (Lumbreras *et al.*, 2015).

The classification of agricultural land suitability in Matopiba was conducted by Lumbreras and collaborators (2015) at a 1:500,000 scale (Figure 1). In this classification, 6 suitability groups are defined, suggesting the type of agricultural use. Groups 1, 2, and 3 represent lands with the best agronomic potential, designated for agriculture. Group 1 includes lands with good suitability, without significant limitations of natural conditions and with high potential for improvement at the adopted management level. Group 2 includes lands with regular suitability, with moderate limitations for production but viable for improvement. Group 3 includes lands with restricted suitability, with strong production constraints, where management costs tend to provide lower profitability. Groups 4 and 5 are appointed for livestock farmings, i.e., unsuitable for agriculture, with the former for planted livestock farmings and the latter for natural livestock farmings or silviculture. Group 6 represents areas without agricultural suitability, which should be appointed for biodiversity conservation and ecosystem services, such as permanent protection areas and Legal Reserve allocation. The reserve category is also presented, comprising protected areas related to Conservation Units, Indigenous Lands, agrarian reform settlements, and afro-descendant territories.

Figure 1 - Agricultural suitability groups of the MATOPIBA region



Source: Lumbreras *et al.* (2015). Elaborated by the authors (2025).

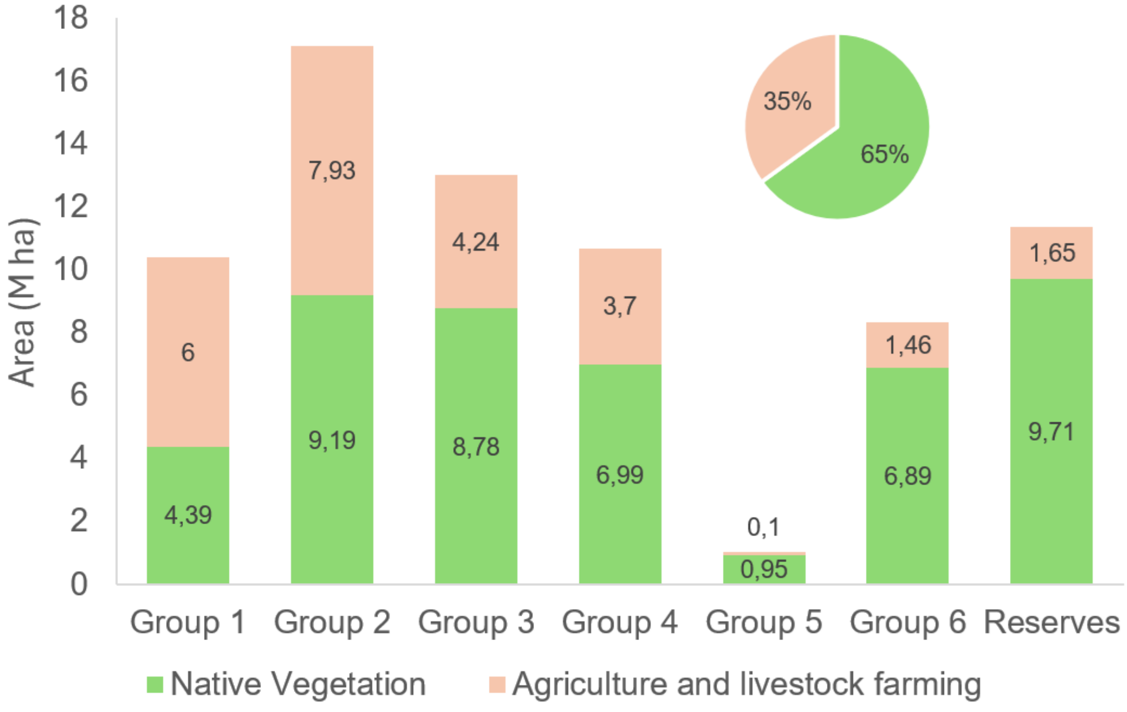
The database regarding land cover and current land use in Matopiba was obtained from MapBiomas (2024), provided at a 30m spatial resolution. The Collection 9 of MapBiomas Project is based on Landsat satellite imagery and includes variables of geomorphology, hypsometry, pedology, vegetation (all at 1:250,000 scale), as well as slope and aspect (30m resolution) to generate current land use class coverage. The deforestation database was obtained from Terrabrasilis (2025) through the Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite (Legal Amazon Deforestation Monitoring Project by Satellite - PRODES), which provides deforestation coverage from 1985 to 2023 at 30m spatial resolution and 1:250,000 scale. All data processing and mapping were performed using Arcmap software, version 10.8 (ESRI, 2019).

The agricultural land suitability classification methodology employed for Matopiba is robust and well-established, providing a critical spatial framework for understanding the region's agronomic potential (Lumbreras *et al.*, 2015). However, it is important to note that the subsequent calculation of native vegetation exhaustion time, often derived from overlaying this suitability map with deforestation rates, represents a simplifying model. This calculation inherently carries uncertainties as it typically extrapolates linear trends from historical deforestation data without accounting for interannual climatic variability, the significant influence of evolving public policies and enforcement, or potential non-linear accelerations and decelerations in land conversion rates driven by socioeconomic factors (Fearnside, 2005; Sparovek *et al.*, 2015). Therefore, the exhaustion time should be interpreted as a projection under a specific set of constant conditions rather than a precise prediction.

LAND USE DYNAMICS AND AGRICULTURAL SUITABILITY

The Matopiba region is predominantly covered by native vegetation, with 25% of its area converted to agricultural use (Figure 2). Among the agricultural suitability groups, Group 2 (lands with regular suitability for crop cultivation) predominates, covering 17.12 Mha. Lands suitable for crop cultivation (good, regular or restricted suitability - Groups 1, 2 and 3, respectively) total 40.53 Mha, of which 18.17 Mha have already been converted to agricultural use. Areas unsuitable for agriculture or livestock farming, recommended for native vegetation maintenance or already designated as reserves, account for 19.71 Mha (of which 3.11 Mha have been converted).

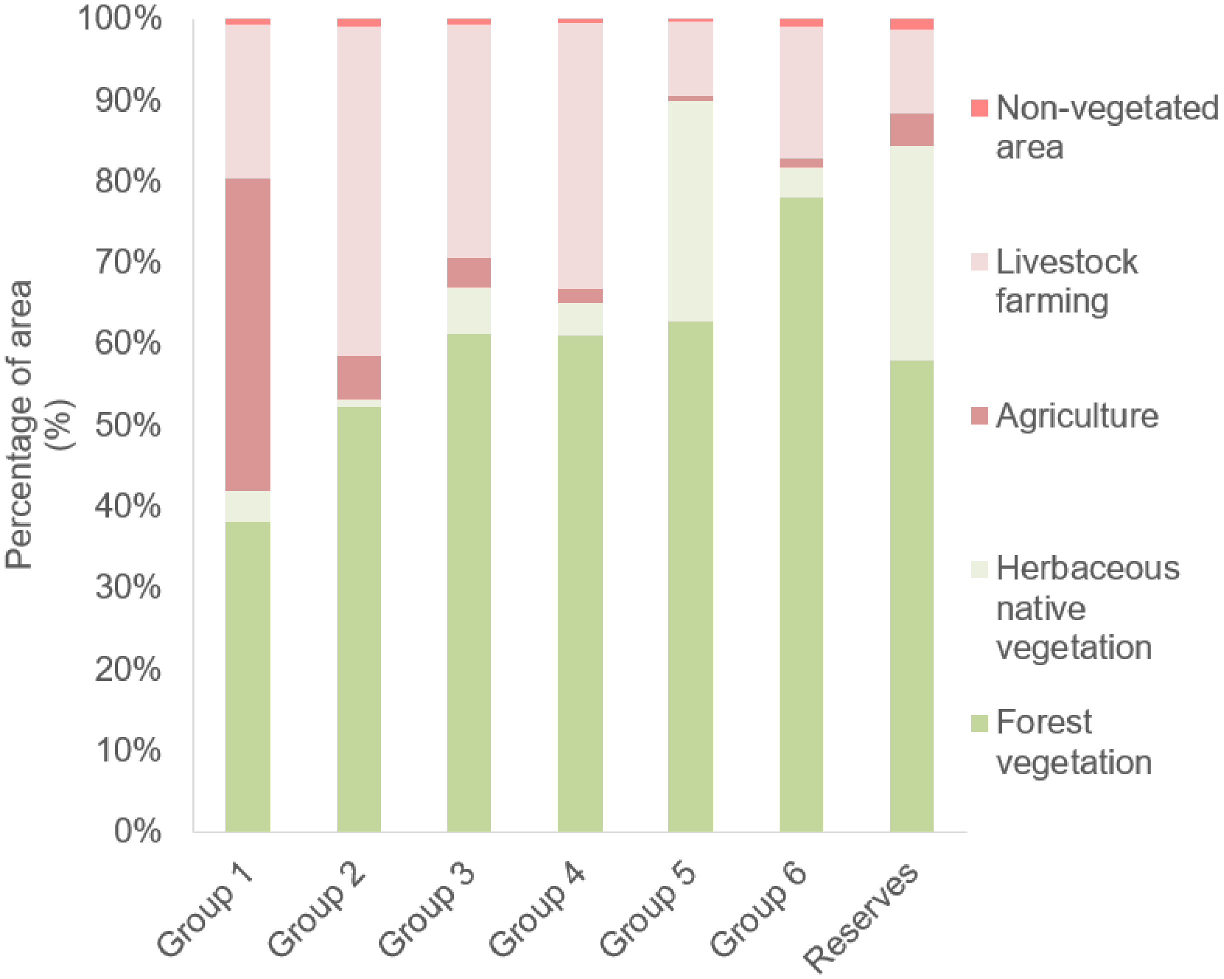
Figure 2 - Total area (Mha) of agricultural suitability groups and their percentage of use in the Matopiba region



Source: Elaborated by the authors (2025).

Group 1, with the highest agricultural suitability, is the only group where farming activity already predominates relative to its total area. Within these activities, livestock farming and accounts for 1.98 Mha, while agriculture 4.01 Mha (Figure 3). This ratio increases significantly in other groups still suitable for agriculture (Group 2, with 7 Mha of livestock farming and 0.94 Mha of cropland; Group 3, with 3.77 Mha of livestock farming and 0.47 Mha of cropland). This scenario reveals that, out of the total 18.17 Mha already in use on lands suitable for agriculture, 12.75 Mha are occupied by livestock farmings.

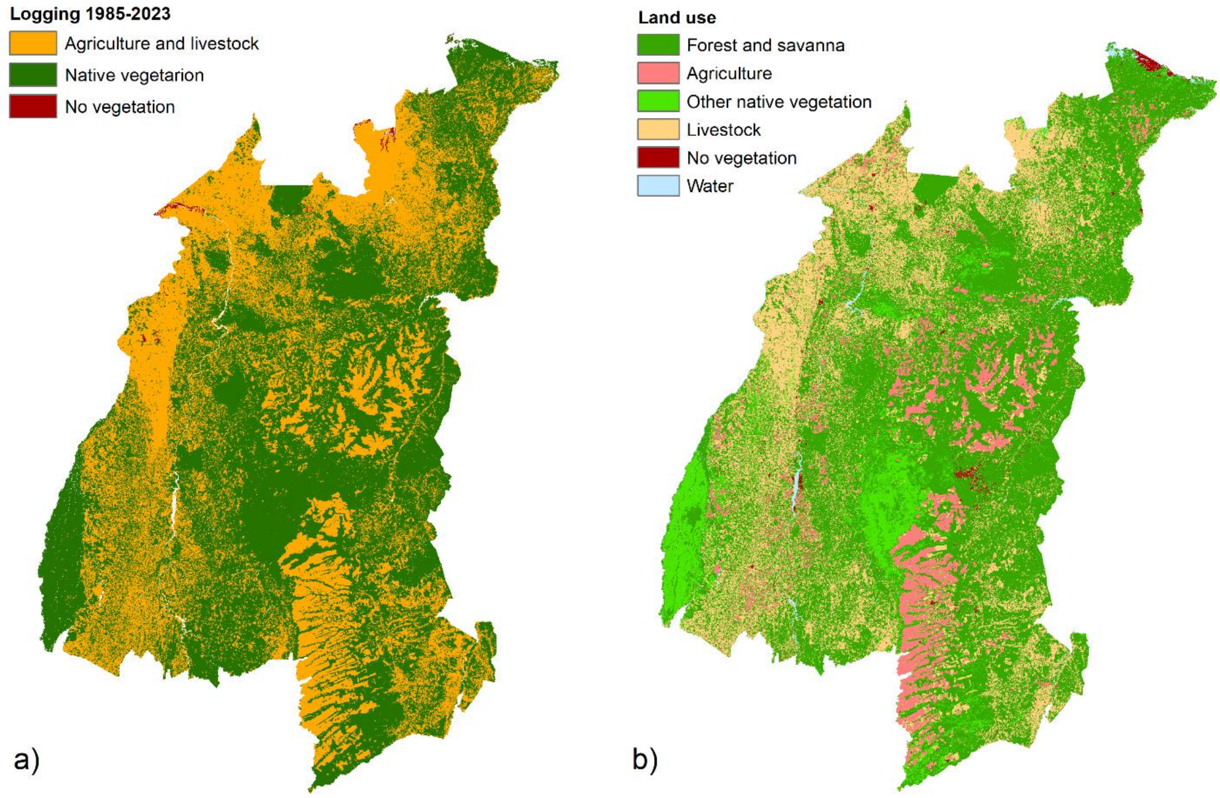
Figure 3 - Distribution of land use classes within agricultural suitability groups in the Matopiba region



Source: Elaborated by the authors (2025).

The conversion of land in Matopiba for cropland or livestock farming use has been widespread, but the most significant transformations occurred in the Bico do Papagaio region in Tocantins and the Cocais Forest in Maranhão. Both are lowland areas where native vegetation was primarily replaced by livestock farmland. In contrast, the plateau regions of Chapadões do São Francisco in Bahia and Alto Paranaíba in Piauí were predominantly converted to cropland (Figure 4).

Figure 4 - Land use changes in the MATOPIBA region- a) Deforestation from 1985 to 2023; b) Current land use and occupation



Source: Terrabrasilis (2025); MapBiomas (2024). Elaborated by the authors (2025).

The advancement of deforestation continues at markedly different rates across agricultural suitability groups. As expected, the highest suitability group (Group 1) showed the greatest conversion of native lands to other uses and maintains the highest deforestation rates (Table 1). Considering the restrictions imposed by the Brazilian Forest Code,Law 12,651/2012 (BRAZIL, 2012), where Cerrado areas may be cleared up to 80% (maintaining 20% as Legal Reserves) and using an average annual deforestation rate (calculated from 2012 to 2023), it is estimated that in 16 years the convertible licensed Cerrado area will be extinct.

Table 1 - Relationship between total area and remaining native vegetation across different agricultural suitability groups in the MATOPIBA region

Agricultural suitability	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Group 5**	**Group 6**	**Reserves**
Total area (Mha)	10,51	17,35	13,16	10,76	1,05	8,41	11,52
Native Vegetation (Mha)	3,49	7,42	8,24	6,16	0,88	6,64	9,44
Rates since 2012 (Mha/year)	0,17	0,16	0,13	0,09	0,01	0,04	0,06

Source: Terrabrasilis (2025); MapBiomas (2024).

SUSTAINABILITY AND CHALLENGES IN AGRICULTURAL FRONTIER EXPANSION

The Cerrado's agricultural production is vital to Brazil's GDP, with Matopiba standing out as a major soybean, corn, and cotton producer. With approximately 4 Mha of soybean cultivation, the region produced a total of 18.5 million metric tons in the 2022/23 crop year, accounting for roughly 12.3% of Brazil's total output (Embrapa, 2025). However, the high rates of native vegetation conversion raise concerns about production sustainability. Deforestation levels in the Cerrado now surpass even those in the Amazon biome (MapBiomas, 2024), and with the highest rates concentrated in Matopiba, the future of native vegetation cover—along with its critical ecosystem services—is under severe threat.

Native vegetation conversion in Matopiba reveals natural resource loss isn't tied to agricultural potential, indicating land underutilization or allocative inefficiency. This is starkly evident in highly suitable areas occupied by low-productivity livestock farmings - Cerrado's least productive land use, generating under one-third of total revenue (Abreu *et al.,* 2013). Rada (2013) confirms this inefficiency, showing that while top farms boosted yields through technology, most properties expanded production mainly by clearing new land - an approach linked to rising production costs (Lima, 2019).

With growing international demand, the expansion of production and increased deforestation may seem inevitable. As predicted by Jevons' Paradox, as resource use - in this case, land - becomes more efficient, its demand rises—and consequently, so does its consumption. However, countering this paradox, Carreira *et al.,* (2024) demonstrate significant results from technological advances (e.g., the introduction of transgenic soybeans in the 2000s), which boosted productivity in previously unsuitable areas. This perspective suggests that deforestation could be curbed while increasing productivity in lands with marginal or restricted suitability, especially when supported by restrictive policies (Carreira *et al.,*2024; Ly, 2025).

Unlike the Amazon, where clandestine deforestation primarily drives livestock farming expansion on public or untitled lands (Torres *et al.,* 2017; MapBiomas, 2024), hindering legal accountability, protective measures in the Cerrado could prove more effective for conservation. Here, deforestation is often linked to agricultural conversion, typically financed by public rural credit programs like those from Banco Nacional de Desenvolvimento Econômico e Social (Brazilian Development Bank - BNDES). In such cases, illegal native vegetation clearance without proper environmental permits can trigger land embargoes by state/federal agencies and suspension of rural credit access - a requirement recently codified in Banco Central do Brasil (Brazilian Central Bank) Resolution No. 5,193 (2024).

To enhance the effectiveness of these measures, it is essential that the provision of rural credit be contingent upon the establishment of activities compatible with the agricultural suitability of the land, as defined by technical mapping, and to avoid allocative inefficiency. However, should current deforestation rates persist, the eradication of native vegetation in areas of high agricultural suitability will become inevitable in the short term, even under the validity of the Forest Code. The projection that native vegetation in high agricultural suitability areas would endure for up to 16 years may be overestimated, given the accelerated pace of illegal deforestation, the ineffectiveness of applied sanctions, and the recurrent issuance of new licenses for vegetation suppression and rural credit concessions, even in cases of repeat offenses (Rajão *et al.*, 2020).

Concurrently with the incorporation of technical agricultural suitability knowledge into environmental legislation, the application of stricter land-use restrictions is essential for maintaining sustainable agricultural production. Since lands with higher agricultural suitability are favorable for establishing various agriculture, with facilitated mechanization and consequently higher financial returns, these areas can be assigned more stringent use restrictions. In this context, a native vegetation retention proportion of 60% is suggested for Group 1 areas, instead of the 20% required by the Forest Code. This approach is expected to reduce deforestation rates to the point of maintaining viable Cerrado coverage for longer than currently estimated. This proportion could be associated with initiatives to restore degraded areas or those with significant environmental liabilities (Sano *et al.,* 2019; Loyola *et al.*, 2021).

Although vegetation cover maintenance is only recommended for Group 6 (unsuitable for agriculture and livestock farming), it is crucial to preserve it across various landscapes of the biome, as biodiversity distribution follows physical and biological attributes resulting from high heterogeneity. Species with greater affinity for more eutrophic soils, such as deciduous seasonal forests in the São Francisco River depression (Arruda *et al.*, 2015; Bueno *et al.* 2018), occur in highly suitable lands but face intense land cover changes. This region is also considered the most demanding of environmental responsibility due to pressure on riparian vegetation (Sano *et al.,* 2019). These riparian forests play a fundamental role in maintaining soil porosity and infiltration, watercourse quality, and especially biodiversity conservation (Nóbrega *et al.*, 2020).

Transforming production systems in the Cerrado – and preserving more natural areas – is critical for addressing climate change impacts already affecting Brazil's agriculture. Native vegetation conversion in the biome drives localized climate shifts, altering rainfall patterns and raising regional temperatures (Leite-Filho *et al.* 2025). Climate suitability projections suggest much of Matopiba's Cerrado could resemble the Caatinga biome within 50 years (Arruda *et al.* 2024).

The impacts of land-use change on biodiversity, ecosystem services, and agricultural productivity are no longer future possibilities but present realities demanding immediate mitigation. Yet, the growing divide between environmental conservation and economic interests becomes increasingly apparent - particularly amid recent proposals to weaken environmental policies (Fernandes *et al.*, 2025). The measures proposed here offer a pathway to maintain Brazil's robust agricultural productivity sustainably while helping bridge this gap.

A comprehensive analysis of Matopiba's land-use future must be expanded beyond linear projections to incorporate alternative scenarios that prioritize sustainable intensification and draw critical lessons from international experiences. A pivotal opportunity lies in the vast areas of degraded and low-productivity pastures, particularly those located on land classified with high agricultural suitability (Groups 1-3). Scenarios focusing on the conversion of these pastures into highly productive agricultural systems or integrated crop-livestock-forestry (ICLF) systems represent a quintessential "land sparing" strategy, potentially meeting production demands while significantly reducing the impetus for new deforestation (Strassburg *et al.*, 2014; Garrett *et al.*, 2018). This approach is further supported by economic models that indicate the potential for agricultural expansion without new clearings through the recovery of millions of hectares of degraded pastureland in Brazil. From an international perspective, valuable benchmarks can be drawn from the analysis of jurisdictional zero-deforestation agreements for cattle ranching in the Amazon, which highlight the critical importance of robust monitoring and supply chain transparency (Lerner *et al.*, 2017) and territorial approaches to consolidate progress in slowing deforestation while providing a framework for addressing important dimensions of sustainable development (Nepstad, 2014). Similarly, examining the successes and challenges of territorial planning and economic incentives for forest conservation in the Moratoriums of the Chaco and Cerrado biomes (Lima; Persson, 2020; Heilmayr *et al.*, 2020) offers critical insights into the governance mechanisms necessary to curb unsustainable expansion (Borras *et al.*, 2012; Byerlee *et al.*, 2017; Kröger; Anja, 2020). Incorporating these multifaceted scenarios and comparative analyses would transition the discussion towards a more nuanced and actionable exploration of pathways that reconcile agricultural development with the imperative of preserving Matopiba's threatened ecosystems.

FINAL CONSIDERATIONS

The Matopiba region contains the Cerrado's highest proportion of native vegetation yet exhibits the biome's highest deforestation rates. While deforestation is most severe in areas of highest agricultural potential, this land conversion fails to yield proportional gains in agricultural productivity, since native vegetation conversion has predominantly given way to livestock farmland - the activity with the lowest economic contribution. Considering the deforestation rate in areas of highest agricultural suitability (0.17 Mha/year), it is estimated that convertible licensed Cerrado areas will be exhausted within the next decade. This allocative inefficiency in the Cerrado results in both the loss of vital environmental resources and the underestimation of economic potential. To address this issue, it is imperative that environmental policies incorporate technical knowledge about land agricultural suitability, coupled with stricter land-use restrictions to ensure maintained agricultural productivity with sustainability.

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Daniel Meira Arruda: Conceptualization, Data Collection, Formal analysis, Maps and Writing; Débora Assumpção e Lima: Conceptualization, Methodology, Formal analysis and Writing, Manuscript revision; Fabio Soares de Oliveira: Methodology, Formal analysis and Writing; Carlos Ernesto Gonçalves Reynaud Schaefer: Methodology, Formal analysis and Writing.