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ESSAY

The trajectory of economic development in the Cerrado: Implications for the environment and health

Trajetória do desenvolvimento econômico no Cerrado: implicações para o meio ambiente e a saúde

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ABSTRACT The article analyzes the trajectory of economic development in the Cerrado, highlighting the socio-environmental impacts resulting from the expansion of agribusiness in the region. It emphasizes the importance of the Cerrado for Brazilian agrifood commodity production, as it accounts for a significant share of the country's Gross Domestic Product (GDP) and exports, while also driving urban growth and job creation. However, as economic progress is intrinsically linked to increased deforestation, greenhouse gas emissions, and the weakening of environmental policies, the Cerrado has become the most threatened biome in Brazil. The article further discusses the Cerrado's vulnerability and that of its rural population in the context of land financialization and resource concentration, which exacerbate inequalities and threaten the region's socio-environmental sustainability. In conclusion, it highlights the implications of this trajectory for the formulation of public policies aimed at a just and sustainable transition, with particular emphasis on the identification of risks to the socioenvironmental health of the biome's traditional populations.

KEYWORDS Cerrado. Development. Agribusiness. Deforestation. Health.

RESUMO *O artigo analisa a trajetória do desenvolvimento econômico no Cerrado, destacando os impactos socioambientais resultantes da expansão do agronegócio na região. O texto ressalta a importância do Cerrado para a produção brasileira de commodities agroalimentares, sendo responsável por uma fatia significativa do Produto Interno Bruto (PIB) e das exportações, além de impulsionar o crescimento urbano e a oferta de empregos. Entretanto, como o progresso econômico está intrinsecamente vinculado ao avanço do desmatamento, emissão de gases de efeito estufa e fragilização das políticas ambientais, o Cerrado transformou-se no bioma mais ameaçado do País. O artigo discute a vulnerabilidade do Cerrado e seus moradores rurais diante da financeirização de terras e da concentração de recursos, agravando desigualdades e ameaçando a sustentabilidade socioambiental da região. Conclui ressaltando as implicações dessa trajetória para a elaboração de políticas públicas voltadas a uma transição justa e sustentável, com ênfase na identificação de riscos à saúde socioambiental para as populações tradicionais do bioma.*

PALAVRAS-CHAVE *Cerrado. Desenvolvimento. Agronegócio. Desmatamento. Saúde.*

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Introduction

> The country that led the most significant agricultural revolution in the tropical world by expanding agribusiness into the Cerrado now bears a global mission and responsibility: to lead the transition toward a healthy and sustainable agri-food system. This entails recognizing itself as a political actor on the global stage (Ricardo Abramovay)[1].

The agricultural sector accounts for approximately 6% of Brazil's Gross Domestic Product (GDP)[2] and about 21% of the country's export value. Agribusiness—which, in addition to primary production, encompasses industry, trade, inputs, and services linked to agriculture—accounts for 23% of GDP[2] and 47% of Brazilian exports, constituting a major driver of trade surpluses and foreign exchange reserves[3].

The Cerrado biome leads national production of major agricultural commodities—including grains, cotton, and beef—supplying one of the country's largest agro-industrial complexes.

Conversely, it was precisely this success that positioned agribusiness as the leading driver of deforestation and greenhouse gas (GHG) emissions in Brazil. According to the National GHG Inventory Report prepared by the Ministry of Science, Technology, and Innovation[4], of the country's total emissions of 2,039,236 kt CO^2 in 2022, 70% are attributable to the tightly interconnected activities of the land-use change and forestry and agricultural sectors (jointly known as Agriculture, Forestry, and Other Land Use – AFOLU)[5]. Owing to its topographic, climatic, and pedological characteristics—and under environmental legislation more lenient than that of the Amazon with regard to the exploitation of native vegetation on private properties—the Cerrado has, for at least five decades, been the biome with the highest deforestation rate relative to its area of distribution. Since 2023, the Cerrado has been the biome with the highest absolute level of deforestation. In 2024, the total deforested area reached 653,000 hectares—approximately equal to that of the Amazon, but roughly double when considered relative to its area of distribution. Moreover, nearly two-thirds of deforestation in the Cerrado shows indications of illegality[6], despite the biome being subject to more permissive land-use requirements regarding the proportion of land that must be preserved (20% in the Cerrado outside the Legal Amazon, compared with 80% required to be protected in the Amazon).

Treated as a 'sacrifice zone', the Cerrado is the biome most exposed to land-use change, as it is composed of sparse vegetation and, consequently, soils highly vulnerable to erosion and water scarcity. Even so, oversight and enforcement of environmental legislation are less stringent in the Cerrado than in the Amazon, facilitating the concentration of essential resources for development and transformation in the hands of elites[7].

Among the dynamics associated with agribusiness expansion, the increasing commodification and financialization of land as a highly profitable asset have raised concern, as they point to a new cycle of unequal wealth accumulation[8]. Grain transport logistics, along with related services and processing industries, generate unevenly distributed benefits, as does the higher per capita income observed in municipalities with greater agro-industrial activity or land concentration. However, because these gains are concentrated in a limited number of municipalities, social inequality remains substantial[9].

The article primarily aims to address the trade-offs between the importance of the biome to the country's economy and its associated socio-environmental implications. In addition, it highlights the trajectory of agribusiness and its impacts on public health, particularly for traditional populations.

From a methodological perspective, this is a targeted literature review on the Cerrado's natural resources and the socio-environmental conflicts associated with the recent expansion of agribusiness in the biome. The study

adopts a temporal scope from 2010 to 2022, a period that coincides with the consolidation of technology-based agricultural policies and the increase in deforestation in the Cerrado. Publicly available secondary data were analyzed, drawn from geospatial platforms such as MapBiomas[10] (irrigation and deforestation), the National Institute for Space Research (INPE)[11] (deforestation and fires), and the Laboratory for Image Processing and Geoprocessing of the University of Goiás (LAPIG)[12] (degraded pastures), together with information from the Department of Informatics of the Brazilian Unified Health System and the Notifiable Diseases Information System (DataSUS/SINAN)[13], the Ministry of Health/Health Surveillance Secretariat (MS/SVS)[14], National Registry of Health Establishments (CNES)[15] and the System of Automatic Data Recovery (SIDRA) of the Brazilian Institute of Geography and Statistics (IBGE)[16]. Institutional documents from the Ministry of the Environment and Embrapa Cerrado were also reviewed to characterize the evolution of public policies targeting both the development and conservation of the biome. The analysis adopted a mixed-methods approach, integrating socio-environmental indicators with a critical content analysis of selected public policy documents, to examine their implications for both human sustainability and the ecological integrity of the Cerrado.

The article first presents an overview of the biodiversity and ecosystem services characteristic of the Cerrado. This is followed by a description of agribusiness-driven transformations, with emphasis on the opening of Brazil's most recent agricultural frontier in the Matopiba region and its implications for the landscape, socio-biodiversity, and public health. It is important to note that the recognition and formalization of land rights for traditional populations (quilombolas, agro-extractive communities, and Indigenous peoples) are fundamental to ensuring access to and sustainable use of natural resources. Subsequently, the prospects for the use of economic instruments to encourage the conservation and/or restoration of native vegetation on private properties are discussed. The conclusion outlines public policies that should be considered to more effectively address socio-environmental and public health concerns in the Cerrado.

The Cerrado

The Brazilian Cerrado is one of the most biodiverse savannas in the world, harboring a vast number of endemic species and playing a crucial role in water provision for most of Brazil's river basins and aquifers. Regarding its flora, approximately 12,000 plant species have been catalogued, of which more than 4,000 are endemic[17]. According to the international non-governmental environmental organization Conservation International, the biome is one of the world's largest 'hotspots'—defined as a global region characterized by exceptionally high levels of endemism and, at the same time, high vulnerability to severe environmental degradation[18]. Biodiversity refers not only to the number of species, but also to the diversity of ecosystem services provided by these habitats. The Cerrado flora includes thousands of plant species with phytopharmacological properties, which are vital to local health and traditional medicine. Its fauna—ranging from large mammals, reptiles, and birds to countless invertebrates—plays an essential role in pollination, seed dispersal, and pest control, all of which are crucial for maintaining ecological balance.

Despite the recognised resilience of Cerrado species and ecosystems, it appears increasingly unlikely that they will be able to absorb the dramatic changes in territories and landscapes, the heavy burden of agrochemicals, and disturbances to soils and hydrological flows, all of which tend to generate growing imbalances[19]. The extensive area of degraded pastures in the biome—estimated at around 68% of total pastureland, or 35 million hectares—is also prejudicial to the sustainability of agribusiness itself[12].

Each year, around 600 million tons of soil are lost through surface erosion on Brazil's agricultural land, generating additional fertilizer replacement costs of approximately R$ 1.3 billion annually, solely to restore lost soil fertility[17]. Accounting for 24% of the country's territory and 38% of national agricultural output in 2015[18], agriculture in the Cerrado may be responsible for proportionally significant economic losses, given the intensity of agribusiness commodity production, which drives higher rates of soil erosion[19]. The growing adoption of more regenerative technologies—such as no-till farming, integrated crop–livestock–forestry systems, and agroforestry—represents a pathway to recover accumulated soil losses and restore essential nutrients.

In addition, Cerrado biodiversity contributes significantly to the maintenance of carbon stocks and carbon sequestration, thereby helping to mitigate climate change. Native Cerrado vegetation, with its deep root systems, is essential for water infiltration and aquifer recharge. It functions as a natural water pump that, through capillary action, helps maintain a shallow water table, facilitating access to water and reducing the costs of cistern-based systems, which are crucial for both human populations and agricultural irrigation and livestock watering[20].

This natural pumping process ensures a continuous supply of good-quality freshwater, essential for sustaining both human populations and agricultural activities. According to MapBiomas Irrigation, in 2023, of the total 36 million hectares used for agriculture and forestry in the Cerrado, only 1.5 million hectares were under artificial irrigation, highlighting the extent to which production depends on rainfall and a high water table[21]. The preservation of these ecosystem services is also vital to support the livelihoods and cultural practices of traditional communities that depend on these natural resources, as well as to maintain the region's ecological health.

As a result of its hydrological functions, the Cerrado biome is considered the 'water cradle' of Brazil, harboring the headwaters of eight of the country's twelve main hydrographic regions. These rivers include the Araguaia, Tocantins, São Francisco, Paraguay, Parnaíba, Gurupi, Jequitinhonha, and Paraná. It is also the biome with the greatest availability of groundwater resources from aquifers, with the three largest in the country (Bambuí, Urucuia, and Guarani) being predominantly located within its territory. However, recent research has estimated that, since the 1980s, the intensification of land use and the removal of native vegetation have led to a delay in the onset of the rainy season of approximately 36 days, alongside a 1.5ºC increase in temperature, resulting in reduced crop yields and undermining prospects for double-cropping systems or the so-called '*safrinha*' maize harvest (the 'second crop'), which has been central to the profitability of agriculture in the biome[22].

Although only about 10% of Brazilian agriculture depends on irrigation, the sector accounts for a disproportionately large share—nearly half—of total consumptive water use, meaning water that is not returned to the environment. This demand is driven mainly by irrigation and livestock watering. Irrigation commonly relies on techniques such as central-pivot sprinkler systems, which are highly efficient at the plot level but require large volumes of water because of the extensive areas they serve. The most rapid expansion of central-pivot irrigation has taken place in the Cerrado, where the majority of water abstraction permits are issued for this purpose[23]. As land-use change progresses and surface water flows diminish, irrigated farming increasingly turns to groundwater to meet its needs. Consequently, water availability for human uses—whether for drinking, livestock, or urban and industrial activities—is becoming ever more constrained, not only for the current population but also for future generations, given the substantial water footprint of agribusiness.

In sum, despite the millennia-long resilience of the ecosystems and peoples of the

Cerrado biome, land-use transformation driven by rampant deforestation and propelled by the expansion of agribusiness threatens the preservation of ecosystem services, often irreversibly. Nearly half (47.9%) of the biome's native vegetation has already been destroyed[24], leading to increased soil erosion, declining water quality and availability, and the disruption of natural processes on which local communities depend. The degradation of these ecosystems may result in the extinction of countless plant and animal species, further undermining the Cerrado's resilience and productivity. Biodiversity loss has direct consequences for ecosystems, with particularly severe effects in transition zones. The decline in biodiversity also affects medicinal plants and food resources that form the foundation of the bioeconomy, negatively impacting the health and income of local populations.

Agribusiness and deforestation

In recent decades, large portions of the Cerrado have been converted to make way for agribusiness, particularly the cultivation of soybeans, maize, sugarcane, and cotton, as well as extensive cattle ranching and eucalyptus plantations. In addition to agribusiness and commercial forestry, the steel and ceramics industries also drive the clearing of native Cerrado vegetation for charcoal production. These land uses, which replace natural vegetation, tend to concentrate in the '*chapadas*'—typically flatter plateaus historically used for free-ranging livestock in the '*Gerais*' (territories of common use) by small-scale family farmers. The '*baixões*' (lowlands), by contrast, function as refuges where traditional communities persist and reproduce their lifestyles, despite growing pressures toward land consolidation[9].

When its trajectory began to take off in the 1970s, large-scale agricultural commodity production faced major constraints due to the nutritional limitations of Cerrado soils, which are typically well structured but low in fertility and highly acidic. Through a public research and development effort led by the Brazilian Agricultural Research Corporation (EMBRAPA), with technical cooperation from the Japan International Cooperation Agency (JICA)—a partner in the Cerrado Development Program (PRODECER)—these barriers were overcome through the application of lime and fertilizers and, later, through Biological Nitrogen Fixation (BNF). These advances enabled large-scale agriculture and livestock production in the Cerrado to achieve competitive levels of productivity.

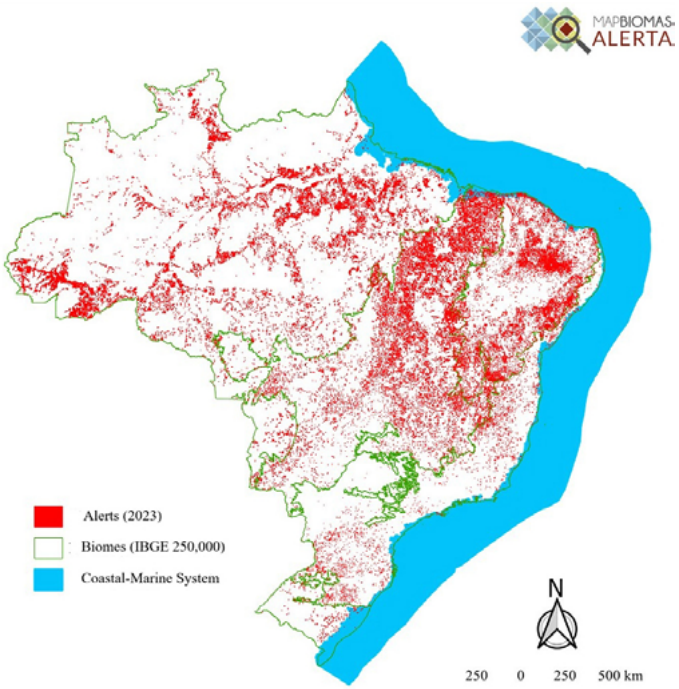
Research in soil microbiology aimed at developing biological nitrogen fixation techniques included the inoculation of bacteria from the genus Rhizobium, carried out under the coordination of Johana Döbereiner at EMBRAPA Agrobiology in Rio de Janeiro, starting in the 1970s. Widely adopted in soybean production systems, seed inoculation with these bacteria allowed BNF to largely replace the use of petroleum-derived nitrogen fertilizers. Although soybean, as a legume, is also capable of fixing nitrogen, bacterial inoculation helped reduce production costs and made Brazilian soybeans more competitive in the global market.

The same principle was applied through the use of diazotrophic bacteria associated with grasses, cereals, and tuber crops. This technology enabled the dissemination of BNF in sugarcane cultivation, reducing production costs and strengthening the competitiveness of Brazilian sugar and ethanol. The use of BNF-supporting bacteria in pastures that incorporate leguminous grasses also contributes to pasture renewal and management, enabling more intensive cattle production systems[25].

In the 2000s, no-till farming techniques, combined with the widespread use of genetically modified seeds (GMOs) under the 'Roundup Ready' brand introduced by Monsanto, enabled the integration of Cerrado agribusiness into the transnational agrochemical complex and interconnected global markets for inputs, machinery, food, and animal feed[26].

It is estimated that, by 2019, human-induced land-use change in the Cerrado had reached 48% of the region. As a result of technical innovations in crop production, in 2024, 75% of legal deforestation in Brazil occurred in the Cerrado[6]. This process involves the removal of native vegetation through burning and the use of heavy machinery (for example, '*correntões*'—chains pulled between pairs of tractors) to clear, uproot, and prepare the soil for cultivation. After vegetation removal, the soil is plowed and treated with fertilizers and pesticides to increase the productivity of agricultural monocultures. Consequently, rural properties registered in the Rural Environmental Registry (CAR) accounted for 95% of all areas where deforestation alerts were detected in the Cerrado in 2022–2023, implying a loss of 620,000 hectares of native vegetation (*figure 1*).

Figure 1. Map of deforestation in the Brazilian Cerrado (2022–23)



Source: Brazilian Deforestation Alert Report (RAD) 2024[6].

This transformation not only threatens local biodiversity but also disrupts the balance of water resources, reducing the soil's capacity to retain water and increasing surface runoff, which can lead to flooding and soil degradation. In addition, the fragmentation of natural habitats resulting from agricultural expansion hinders the survival of many native species and reduces ecosystem resilience. The replacement of native vegetation with agricultural monocultures also contributes to the release of large volumes of greenhouse gases (GHGs), further driving climate change.

In response, the federal government has mobilized resources to encourage crop diversification through Integrated Crop-Livestock Systems (iLP), including Integrated Crop-Livestock-Forestry (iLPF) components. However, critics argue that these systems have not gone much beyond sequential land use, failing to achieve genuine integration that would reduce pressures for the expansion of

conventional practices. Others counter this view, instead advocating systemic intensification of land use in the Cerrado as a means of easing pressure on forests in both the Cerrado and the Amazon[27].

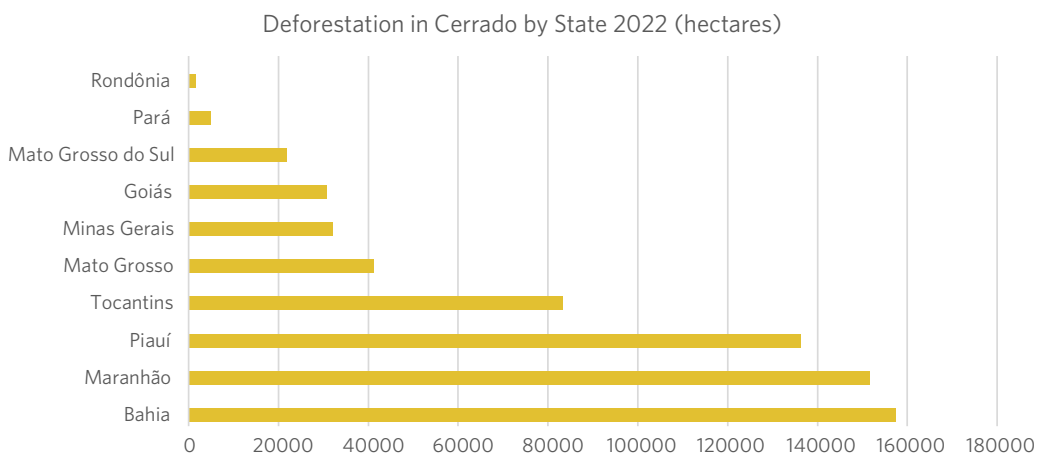
In sum, land-use change in the Cerrado has profound and far-reaching effects, threatening both the ecological integrity and the economic sustainability of the region. Predatory exploitation has produced locally deleterious effects, such as soil compaction and the loss of fertility and moisture. These impacts, combined with prolonged drought conditions and rising temperatures driven by climate change, as well as a strong and growing dependence on imported petroleum-based inputs—fuels, fertilizers, and agrochemical solvents—have undermined the very viability of commodity production itself.

Soybeans—the flagship crop of Cerrado agriculture—illustrate these dynamics. Over the past 30 years, the use of agrochemicals has increased more than eightfold, disproportionately to gains in area and productivity, sharply reducing producers' profit margins. This has been demonstrated by research from the Instituto Escolhas, which estimated a proportional decline in pesticide-use efficiency from 1 kg per 22 sacks of soybeans in 1993 to 1 kg per 7 sacks in 2023[28]. Although Brazil ranks third in performance compared to other major global soybean producers (the United States of America, Argentina, China, and India), it has, since 2011, been the country with the highest pesticide consumption per sack of soybeans.

MATOPIBA and other sub-regions

The MATOPIBA region, which encompasses the entire state of Tocantins and parts of the states of Maranhão, Piauí, and Bahia, has been the most affected area of the Cerrado in terms of deforestation over the past decade. In 2024, the region accounted for 42% of all deforested area in the country and 79% of native vegetation clearing in the Cerrado (*graph 1*). Agricultural expansion in this region has been particularly intense in Ma ranhão and Piauí, where a large share of recent deforestation has been concentrated, resulting in habitat destruction and species loss, as well as the intensification of land conflicts involving Indigenous and Quilombola populations.

Graph 1. MATOPIBA's share of deforestation in Brazil in 2022



Source: MapBiomas[24].

Transition zones (ecotones) between the Cerrado and other biomes, such as the Amazon and the Caatinga, are of great importance due to their high diversity of plant and animal species. This is because, in these contact zones, different biomes interact, resulting in a mixed environment that supports species adapted to intermediate conditions. The ecotonal area associated with the Cerrado is larger than that of some of Brazil's biomes: 'the Cerrado–Amazon ecotone, for example, covers 4.85% of the country, making it larger than the *Campos Sulinos* (southern grasslands) and Coastal biomes, and the Cerrado–Caatinga ecotone covers 1.3% of the national territory'[29].

The expansion of agribusiness in MATOPIBA has been underway since the early 2000s, but the regulation of land occupation in the region's agricultural zone was largely neglected by public authorities due to political factors and the lack of prioritization of promised funding. Instead, the private sector itself took on the development of multimodal transport corridors complementary to public logistics systems, enabling the export of commodities produced in the region's interior. As a result, in the first decade of the twenty-first century, with the support of research on soil correction and fertilization and advances in agricultural technology, MATOPIBA became the main region for soybean expansion, as well as a significant producer of cotton and maize[30].

Heightened attention to MATOPIBA is warranted, as is the emergence of a new soybean frontier in Cerrado zones within the Amazonian states of Amapá and Roraima. These new frontiers extend a long historical process of Cerrado occupation that began in the 1970s in the Triângulo Mineiro region in the States of Minas Gerais, Goiás, and Mato Grosso do Sul. Indeed, PRODECER I—the program that first introduced the tropical soybean technological package to the Cerrado—was initially disseminated in these states in a pioneering manner. Following the first expansionary wave of Cerrado agribusiness, it was argued that the occupation model should follow a 'land-saving' approach, whereby intensive production in the Cerrado would be complemented by large preserved areas in both the Cerrado and the Amazon[26].

However, despite the Cerrado covering nearly one quarter (23.9%) of Brazil's total territory, there is a clear stagnation in the expansion of protected areas within its boundaries. The biome's high ecological value is poorly reflected in its protection status. Only 9.2% of the Cerrado is under some form of public protection, as represented by Conservation Units (UC)—excluding Indigenous and Quilombola territories—and only 2.8% (5.6 million hectares) is classified as Strict Protection Conservation Units (e.g., national parks, biological reserves, ecological stations, etc.). Meanwhile, 6.4% (12.9 million hectares) falls within Sustainable Use Units[31], mainly Environmental Protection Areas (APAs). While the 192 officially recognized Private Natural Heritage Reserves (RPPNs) in the region protect just over 163,000 hectares across the vast Cerrado, the 216 Indigenous Territories cover approximately 8.3 million hectares, corresponding to 4.1% of the biome.

Although the number of federal Conservation Units (UC) is nearly equal to that of state-level UCs, there are twice as many state-level Strict Protection Conservation Units (PI) as federal ones in this category. In contrast, the 23 federal PI units cover twice the area of the 107 state-level units in the same category, with an average size of 170,000 hectares per federal unit versus 16,000 hectares for state units. By contrast, in the case of Sustainable Use Units (US), state-level units cover an area four times larger than the same category under federal management, reflecting the fact that most UC in this category are Environmental Protection Areas (APAs)—a designation also commonly applied to municipal Conservation Units (UC)[31]—characterized by comparatively weak management regimes when contrasted with Strict Protection UC.

Due to insufficient protection of remaining Cerrado areas within Conservation Units, the

implementation and enforcement of Legal Reserve (RL) requirements—20% mandatory protection for rural properties located in the Cerrado biome outside the Legal Amazon and 35% for those within its boundaries—are crucial to ensuring the conservation of remaining vegetation and the environmental sustainability of the region. Currently, 62% of native Cerrado vegetation lies within rural properties subject to the Brazilian Forest Code[32]. In this context, private properties in the Cerrado that maintain the required proportion—or more—of RL play a key role in biodiversity conservation and water resource protection, as well as in mitigating the negative impacts of dominant agricultural and livestock activities in the region.

Despite being perceived as essential, the protection and restoration of native vegetation on private lands lack adequate financial incentives. There is growing interest in the creation of instruments such as Payments for Environmental Services (PSA), as well as subsidized credit mechanisms like the Low-Carbon Agriculture Plan (ABC Plan), 'green bonds', and other financing tools to support the restoration of degraded pastures. However, the ABC Plan lacks significant funding within its credit lines dedicated to the restoration of Permanent Preservation Areas (APPs) or Legal Reserves (RL) on private properties. Since the conservation of at least 20% of native vegetation is mandatory under the Brazilian Forest Code (Law No. 12,651/2012), monitoring and enforcement of remaining private forest areas in the Cerrado operate largely in a punitive rather than incentive-based manner. A survey of sixty-nine soybean farmers across the four MATOPIBA states found that most would be willing to accept payments in exchange for preserving intact forest resources, even when the law permits the clearing of a substantial portion of these areas[33].

The cost of such payments may represent an excessive burden on public finances when compared to the returns from monoculture, making it difficult to maintain native vegetation beyond the area legally required. On the other hand, according to EMBRAPA researchers, the Brazilian agricultural production model is based on an abundance of land, which allows the simultaneous expansion of both production and productivity, as well as an abundance of ecosystem services, particularly rainfall-dependent water supply, climate regulation, soil protection, and pollination[34].

Thus, it is important to acknowledge that at least part of the success of Brazilian agriculture depends on the provision of ecosystem services. For instance, around 90% of Brazilian agricultural production lacks irrigation systems and depends exclusively on natural rainfall patterns. This figure rises to nearly 98% in the case of livestock farming[23]. It is therefore essential that public policies and conservation initiatives be strengthened in order to ensure that the proportion of protected land continues to increase, helping to reduce the imbalance between agricultural production and environmental conservation[35]. This also requires, above all, recognition of the importance of native vegetation on rural properties as a provider of essential inputs, whose substitution—for example, through irrigation—may entail costs exceeding the opportunity cost of maintaining Legal Reserves.

The Brazilian financing system for operating costs, investment, processing, and commercialization in the agricultural sector—detailed annually in the Plano Safra (Harvest Plan)—allows the Central Bank and public banks to transfer part of credit operations to private financial agents, creating mandatory financial allocations directed to the agricultural sector[36]. Government sources indicate that subsidized taxation to agribusiness result in an annual loss of approximately R$ 158 billion in federal tax revenue, equivalent to the annual budget of the Bolsa Família Program. The paradox is that these foregone revenues primarily benefit multinational companies engaged in export-oriented production, without translating into lower prices for domestic consumers[37].

Another important aspect is the need to consider the broader agro-industrial landscape

beyond the Cerrado and its spatial repercussions. There is an expectation that the expansion of agribusiness in the Cerrado may, in some cases, reduce pressure on the Amazon by directing agricultural activities toward already altered areas. However, this expansion must be carried out in a sustainable manner so as to avoid accelerating degradation within the Cerrado itself. The central hypothesis underlying this perspective is that sustainable intensification of agriculture in the Cerrado can help reduce the pressure to open new frontiers in both the Amazon and the Cerrado[38].

The hypothesis that intensifying internal agricultural frontiers may reduce pressure on better-preserved regions is controversial and requires further investigation. For example, from the perspective of scholars of the Amazon region, the rebound effect associated with the so-called Jevons paradox—where greater efficiency in agricultural practices, rather than reducing pressure, leads to its increase—would result in the expansion of frontier exploitation. Indeed, existing studies provide evidence that the intensification of the most profitable land uses tends to increase their spatial spread rather than confining them spatially[26].

In contrast, the conventional perspective based on historical production function analyses of Brazilian agriculture suggests that a 100% increase in the sector's gross output can be proportionally explained by technology (68%), labor (23%), and land (9%)[39]. Based on this analysis, the expansion of agricultural frontiers in the country can be characterized as 'land-saving'. However, this conclusion depends strongly on the activity considered. In the case of livestock production, for example, technical inefficiency in the use of production factors is quite high, at around 27%, with land being the main source of inefficiency and therefore significantly underutilized[40].

A recurring response from the agricultural sector involves the transition of production systems toward 'regenerative agriculture', in which practices such as no-till farming are combined with reduced use of agrochemicals and the restoration of degraded areas, and are compensated through increased soil carbon content. To encourage and support such transformations, price premiums for commodities would be required. However, the feasibility of this transition depends on the availability of technical assistance, financing, and appropriate insurance mechanisms, as well as on integration with carbon markets[41].

As a trading partner of the European Union (EU) in commodities whose origins have been traced to farms in the Cerrado, Brazil has been classified by the EU as a 'standard risk' country among exporters of agricultural commodities associated with deforestation[42]. In other words, agricultural products covered by the European Union Deforestation Regulation (EUDR) originating in Brazil (soy, coffee, cocoa, palm oil, beef, rubber, and timber, as well as their by-products) will be subject to due diligence requirements to assess and trace potential 'contamination' with deforestation, and may consequently be prohibited from entering the EU market. Operators and traders importing from Brazil will be required to conduct full due diligence, including risk assessment and mitigation measures at the point of origin, to ensure that their products are deforestation-free and compliant with the EUDR[43].

The Cerrado, being a biome with low tree cover where deforestation remains legally permitted outside the areas defined by the Forest Code, is not classified as "forest" under the EUDR, which—following the definition of the Food and Agriculture Organization of the United Nations (FAO)—defines forest as land with at least 10% tree cover and a minimum canopy closure of 10%. However, the EU has chosen not to establish subnational or regional risk classifications within countries in order to avoid leakage and the displacement of commodities or livestock production to areas considered lower risk.

The lack of a clear forest classification for the Cerrado under the EUDR effectively places it in a more vulnerable position than the Amazon in the face of the forces driving

the opening of new frontiers in recent years, particularly in the so-called '*lavrados*' or 'Amazonian Cerrado' areas of Amapá and Roraima. Although these areas do not belong to the Cerrado biome, they constitute large patches of savanna surrounded by forest, remnants of glacial periods.

It is expected that such regulation will encourage better practices. However, the most likely outcome is that Brazil will redirect its exports to China, which is among the countries that have most heavily financed the export of commodities originating from deforested areas in recent years[44]. China has been increasing its attention to the traceability of tropical imports, although it has not formally adopted any restrictions on imports of commodities associated with deforestation[45].

Critical assessment of public policies in the Cerrado

Development policies applied to the Cerrado since the 1970s reveal a pattern of incentives favoring agricultural expansion without consistent integration with environmental and social policies. The PRODECER program was central to enabling agricultural modernization, but it neglected environmental conservation and the social protection of local populations[46].

The ABC Plan, launched in 2010, sought to encourage sustainable practices such as no-till farming and pasture restoration. However, it concentrated its resources on large-scale producers. Assessments by the Ministry of Agriculture[47] indicate that less than 8% of ABC+ financing was allocated to family farming.

In the health sector, the National Plan for the Reduction of Agrochemicals (PRONARA), proposed in 2012 and only regulated in 2025, still faces budgetary constraints and political resistance to its effective implementation[48]. Despite foreseeing intersectoral actions involving the Ministries of Health, Environment, and Agriculture, the plan lacks monitoring indicators and territorial targeting.

Other initiatives, such as the Payments for Environmental Services Program[49] and the Forest Code, have introduced instruments for private conservation, but with limited practical reach: as noted above, only 2.8% of the Cerrado's total area is under Strict Protection (PI)[50], although current management efforts seek to address this situation through the designation of new Conservation Units (UC) and Indigenous Territories (TI). The lack of consistent environmental governance and enforcement limits the effectiveness of these policies, perpetuating institutional fragmentation[51].

In summary, existing policies fail to articulate economic, environmental, and social dimensions in an integrated manner, treating each dimension in isolation. In this sense, the integration of agroecology policies, land tenure regularization, and environmental health is a necessary condition for an effective socio-ecological transition[52].

Land tenure and health issues in the Brazilian Cerrado

Historically, land concentration in Brazil resulted from the extensive use of native pastures, whose carrying capacity is significantly lower than that of African and Australian grasses, supporting no more than 0.4 AU/ha[53]. This preference for a land structure dominated by large estates was formalized in the 1850 Land Law (*Lei das Terras*), which required cash payment for public lands and formal titling, effectively excluding formerly enslaved people and family farmers. As a result, only the largest cattle ranches were able to remain economically viable and, through privileged access to land via public auctions or land grabbing (*grilagem*), expanded their control over small and medium-sized properties[54].

Over recent decades, the expansion of soybean–maize double cropping and cotton production, closely tied to global commodity markets, has operated under economies of scale, reinforcing land concentration through farms spanning between 10,000 and 30,000

hectares. With the rise in prices of chemical inputs and fossil fuels triggered by the COVID-19 pandemic—reaching a weighted average increase of 34.7% for small-scale producers[55]—and the growing frequency and severity of droughts and shifts in rainfall regimes, thousands of judicial recovery proceedings involving small and medium-sized enterprises linked to agriculture and related services have been recorded across the Cerrado. The acquisition of these enterprises by large conglomerates—including land purchases by foreign investors in partnership with domestic capital—has further intensified land concentration[56].

This process of land reconcentration particularly affects small farmers and traditional communities, such as *geraizeiros*, who practice collective land use and small-scale farming, and those living in *fundos* e *fechos de pasto* (literally, bottom and back borders of pastures), represent customary communal grazing systems used by rural populations in the region. The MATOPIBA region, together with the states of Bahia and Maranhão, hosts the largest populations of quilombolas, accounting for more than 50% of all declared descendants of enslaved people in Brazil, most of whom live outside officially recognized quilombo territories due to delays in land demarcation[57]. In recent years, these communities have increasingly become sites of land conflicts with agribusiness actors, as illustrated by the following quote:

> Border regions are never empty. They are home to a rich array of communities, cultures, and economies that do not sit comfortably within the neoliberal economic paradigm imposed on so-called sacrifice zones. As a result, territorial sacrifice inevitably entails sociocultural sacrifice for the marginalized groups who inhabit these borderlands[7](103972).

The Cerrado remains a vital source of food security for small-scale family farming, despite ongoing land reconcentration and tenure conflicts. At the time of the 2017 Agricultural Census, the region was home to roughly 600,000 family farmers cultivating more than 20 million hectares, generating an income of R$20.4 million[58]. Even so, small and medium landholders have increasingly been displaced or pressured to sell their land at undervalued prices. This process reduces the land available for family agriculture, which is essential to local food security and to the preservation of sustainable farming practices[59].

In addition to lands that have not yet been formally recognized, the biome contains 95 officially demarcated Indigenous Territories covering 96,000 km²—equivalent to 4.8% of the Cerrado as a whole. This area does not include the portions of the Cerrado encompassed by the 304 Indigenous Territories nationwide that are still awaiting formal recognition, with their processes stalled under the Marco Temporal. This legal framework ties Indigenous land rights to occupations in place as of the 1988 Constitution, and serves as a means to restrict permanent demarcation of additional Indigenous lands claimed by their original inhabitants, thus playing into the hands of agribusiness interests that compete for these territories. The region also includes 44 quilombola territories covering nearly 4,000 km², as well as other traditional territories that remain unmapped or unregistered[60].

Beyond the delays in the formal recognition of ancestral territories, traditional communities face growing obstacles to accessing essential natural resources such as water and extractive products—including babassu palm nuts (*Attalea spp.*), timber, flowers, fruits, and a wide range of raw materials needed for subsistence, cultural reproduction, or small-scale commercial production. These constraints directly undermine their living conditions. Land loss also drives forced migration to urban areas, where these groups are often confronted with precarious housing and employment opportunities.

A survey conducted for the Socioenvironmental Institute (ISA) in partnership with the National

Coordination for the Articulation of Rural Black Quilombola Communities (CONAQ) indicates that 98.2% of quilombola territories are threatened by infrastructure projects, mining developments, and overlaps with private land claims. Moreover, 1,385 mining claims place pressure on 781,000 hectares of quilombola territories, and over 15,000 rural private property registrations overlap with quilombola lands[61].

To address these land tenure challenges, public authorities must implement policies that promote land regularization, the protection of community lands, and support for family farming. In addition, regenerative agriculture initiatives and sustainable farming practices can help mitigate the negative impacts of agribusiness and ensure a more balanced and equitable use of land in the Cerrado—although it is evident that technology alone does not have the capacity to offset these impacts at the required scale without securing access to land and other essential natural resources for life.

Social impacts and health

Traditional communities living in the Cerrado, such as quilombolas, Indigenous peoples, and small-scale farmers, face significant challenges due to deforestation and the expansion of the agricultural frontier driven by large-scale enterprises. The loss of land, the degradation of natural resources, and pressure from agribusiness threaten both the livelihoods and cultural practices of these communities. These factors also contribute to a rise in health problems, including malnutrition, diseases transmitted through contaminated water, and psychological stress. A territorial approach to health and development issues has been emphasized in the work of Rigotto and Augusto[62], serving as a reference framework for research projects on public and collective health and sociobiodiversity in the Cerrado.

The concept of socioenvironmental health emerges from the need to understand the connections between ecological processes and the social determinants of health. According to Porto[63] and Rigotto et al.[64], this approach recognizes that environmental degradation and territorial inequalities act as structural determinants of health, giving rise to patterns of illness linked to prevailing models of production and land use.

One crucial and often overlooked aspect is the impact of environmental degradation resulting from deforestation and unsustainable agricultural practices on public health, significantly contributing to the spread of disease. Biodiversity loss, for example, facilitates the emergence of new zoonoses—diseases transmitted from animals and invertebrates to humans. Soil and water pollution, associated with the indiscriminate use of pesticides and fertilizers, contaminates drinking water sources and compromises the quality of food production, increasing the risk of gastrointestinal diseases and other health conditions.

The annual report on apparent national consumption of active ingredients in agrochemicals and biological products in Brazil shows that the country is the world's largest consumer of these substances. The FAO maintains a registry of the declared volumes of pesticides and active ingredient raw materials imported by member countries[65]. Brazilian data and reports have been compiled since 2009 in accordance with the requirements of Article 41 of Decree No. 4,074/2002, which regulates the use and transport of agrochemicals in the country[66]. As the largest user of pesticides in the world—surpassing the United States, the European Union, Mexico, and other major agricultural producers—Brazil faces a range of comorbidities associated with human exposure to these agrochemicals.

Previous studies have shown that the volume of pesticides applied per cultivated hectare in the country increased by 427% between 1991 and 2015[67]. The growing resistance of invasive weed species to conventional herbicides used in large-scale monocultures in the Cerrado and other productive regions

has led to their replacement by more potent agrochemicals, some of which are banned in Northern Hemisphere countries. From 2015, the World Health Organization (WHO) classified glyphosate, the active ingredient in Roundup®, as 'probably carcinogenic to humans', and its use in public spaces (parks, streets, etc.) had been prohibited since 2013[68]. The spraying of crops with these substances has harmed the health of both agricultural workers and nearby residents[69].

To illustrate these dynamics, *table 1* presents estimated average values for the Cerrado biome, compiled from a range of official secondary data sources.

Table 1. Indicators of environmental pressure, institutional capacity, and health impacts in municipalities of the Cerrado biome, 2010 and 2022

Dimension	Indicator	Synthetic Definition	2010	2022	Variation	Source
Environmental pressure	Deforested area in the Cerrado (km²/year)	Annual area of native vegetation suppression detected by remote sensing	6,469	10,688	+ 65%	Inpe – Prodes Cerrado; MapBiomas; Lapig[10–12]
Health outcomes	Mortality from pesticide poisoning (per 100,000 inhabitants)	Mortality rate from pesticide poisoning (ICD-10 X48 + Y18)	0.27	0.50	+ 83.2%	SIM/DataSUS[14]; IBGE[16]
Healthcare capacity	Mortality from respiratory diseases (per 100,000 inhabitants)	Mortality rate from respiratory diseases (ICD-10 J00–J99)	57.76	80.46	+ 39.3%	SIM/DataSUS[14]; IBGE[16]
Environmental institutional capacity	Hospital beds (per 1,000 inhabitants)	Total number of hospital beds per 1,000 inhabitants	2.60	2.44	- 6.1%	CNES/DataSUS[15]; IBGE[16]
Primary Health Care	Proportion of SUS hospital beds (%)	Percentage of hospital beds affiliated with the SUS relative to the total number of beds	73.6	69.0	- 4.6 %	CNES/DataSUS[15]
Environmental pressure	Municipalities with environmental surveillance (%)	Percentage of municipalities with a registered environmental surveillance service in the CNES	7.39	38.21	+ 417%	CNES/DataSUS[15]
Health outcomes	Potential coverage of Primary Health Care (%)	Percentage of the population potentially covered by PHC teams	74.76	81.95	+ 7.19 %	Ministério da Saúde – Relatório APS[15]

Source: Own elaboration.

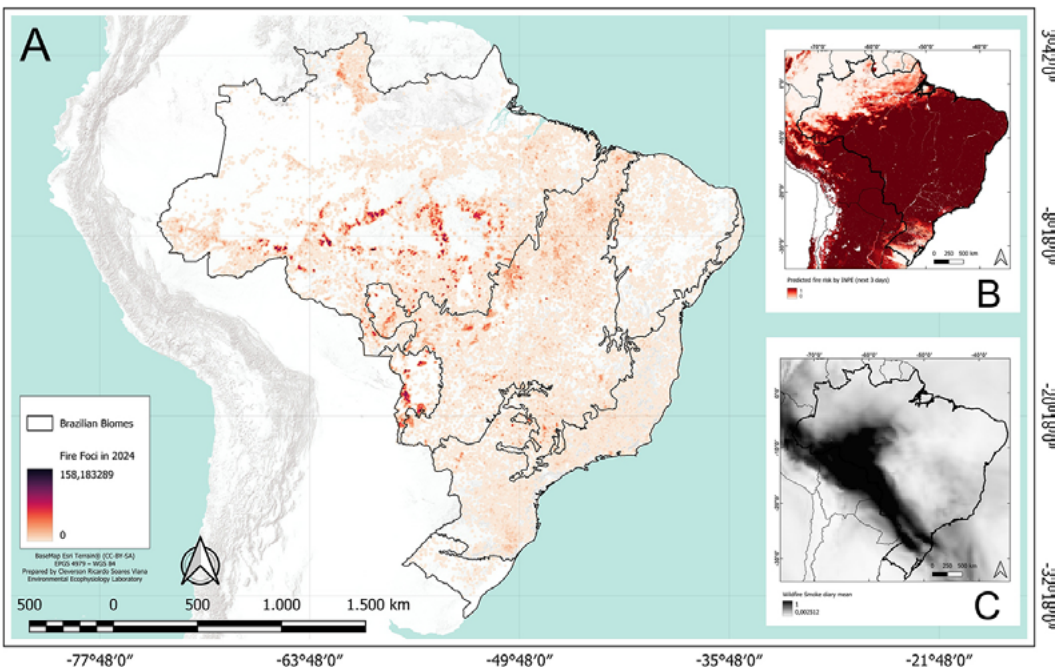
Note: Rates were calculated per 100,000 inhabitants using records from SIM/DataSUS and population data from the Demographic Censuses of the IBGE (2010 and 2022). Data on hospital beds, the proportion of SUS-affiliated beds, and environmental surveillance were obtained from the National Registry of Health Establishments (CNES). The presence of environmental surveillance was assessed based on the existence of at least one establishment with a Health Environmental Surveillance service registered under code 141003 (Service 141 – Health Surveillance; Subtype 003 – Environmental Surveillance). Municipalities were considered to have active environmental surveillance if they reported one or more such records in the respective year. Potential primary health care coverage was extracted from the PHC Reporting System of the Brazilian Ministry of Health. Annual deforestation data were obtained from the PRODES Cerrado system of the INPE. All indicators were aggregated for the 1,434 municipalities with territorial overlap with the Cerrado biome.

The results in *table 1* reveal a significant increase in deforested area, occurring alongside a rise in mortality from respiratory diseases and pesticide poisoning. This worsening scenario takes place in a context of persistent insufficiency in environmental surveillance, as only just over one-third of municipalities (548) had formally registered services in the CNES in 2022, highlighting structural limitations in the state's capacity to monitor and address environmental health risks. In addition, the reduction in the availability of hospital beds and in the proportion of beds within the Unified Health System (SUS)

points to a weakening of the health system's capacity to respond to the growing burden of environmentally determined illness, even though an expansion in the potential coverage of Primary Health Care (PHC) is observed. Taken together, these findings point to a process of socioenvironmental vulnerability in the Cerrado, in which the dynamics of agribusiness expansion and land-use change advance at a faster pace than the capacity for environmental regulation, health surveillance, and health-related interventions.

Moreover, the destruction of natural areas directly affects air quality. Burning practices and the emission of pollutants from agricultural machinery and the livestock industry contribute to an increase in respiratory problems among the local population, particularly children and older adults. This issue is aggravated by climate change, which can trigger large-scale wildfires, as observed during the 2021–2024 period. The impact of smoke from forest fires extends beyond agricultural frontiers, spreading across Brazil and into neighboring countries (*figure 2*).

Figure 2. Maps of burned area (A), fire risk (B), and smoke plume from forest fires (C) for the year 2024 across Brazil and neighboring countries in South America



Source: Sobreira et al.[70] and Inpe[71].

The main concern lies in the fine particulate matter (PM2.5) present in smoke, which has significant health implications. Besides, toxic and carcinogenic compounds pose a major risk to both urban and rural communities, including traditional peoples. The implications of climate change associated with forest fires in future projections represent a high and potentially catastrophic risk to human health, particularly for the most vulnerable groups, such as older adults, children, pregnant women, and people with chronic diseases, which in many cases can lead to death[70]. These issues also significantly worsen the fiscal burden at the subnational level, as a large share of health-related costs is borne by state and municipal administrations[72].

From a critical perspective on the territorialization of impacts of modern agribusiness and its effects on health:

> In the territorial dynamics of agribusiness, there is a clear production of expropriation and alienation [...] in which individuals are deprived of the conditions for autonomous reproduction, preventing them from benefiting from socially produced technology in ways that could enhance knowledge and practices conducive to a sustainable socio-metabolism between society and nature. Instead, their lands are taken, their rivers are contaminated, and a monochromatic landscape of agro-export monocultures is imposed, along with pasture voids or mining craters, resulting in the erosion of life's meaning within reified social relations—subsumed under the reproduction of capital[73](23).

In contrast, it is expected that the development of markets for products derived from sustainable practices will not only foster a regenerative economy but also improve public health by encouraging healthier production methods and reducing dependence on harmful chemical inputs. The recognition and valuation of the environmental services provided by the Cerrado—such as climate regulation and water purification—also has a direct positive effect on the health of communities that depend on these ecological functions.

In summary, land tenure and health issues in the Cerrado are complex and require an integrated approach that takes into account both social and environmental dimensions, ensuring the protection of the rights of traditional communities and the sustainability of the region's natural resources.

Conclusions

As previously discussed, although inequality remains significant, the rapid expansion of agribusiness in the Cerrado has driven social and economic development in some municipalities. On the other hand, soil degradation and the depletion of aquifers are consequences of this development trajectory.

As instruments that guide the actions of actors in conflict, public policies should indicate pathways capable of resolving, or at least mitigating, the problems arising from these disputes. In this context, two factors are critical: the intensity of land use and the rapid pace of expansion of agricultural and extractive frontiers. Against this backdrop, it becomes urgent to ensure the formal recognition of land rights for traditional communities, guaranteeing their access to land and the preservation of their ways of life; and to regulate the use of water resources, through measures that prevent overexploitation and ensure the sustainability of Cerrado ecosystems.

The adoption of sustainable practices that effectively function as integrated systems, such as Agroforestry Systems (AFS), is imperative not only to preserve the environment but also to ensure healthy food and the well-being of future generations. These goals should be reflected in government policies, such as the Plano Safra, aiming to encourage investments in the restoration of Legal Reserves and Permanent Preservation Areas, regenerative agriculture, organic production, and Agroforestry Systems, as well as allocating a larger share of subsidized credit to family farmers who adopt agroecological practices.

Protecting the population from the risks of exposure to agrochemicals requires implementing stricter standards for their use, alongside the promotion of sustainable production and consumption practices. These measures are provided for under PRONARA, a decree aimed at fostering integration between human and environmental health in order to make the agricultural model safer and more ecologically balanced.

The analyses conducted in this study reinforce the need to build a just transition strategy

for the Cerrado, which requires the adoption of integrated territorial planning that recognizes the role of ecosystem services in sustaining the agricultural economy and the population's well-being.

Authorship contributions

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