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A Sustainability Index for Agrarian Expansion: A Case Study in Mato Grosso (Brazil)

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Abstract: Since the early 2000s, sustainable development in agriculture has attracted substantial political attention, institutional support, and financial commitment, raising expectations for tangible outcomes. Yet, measurable progress remains uneven. As a leading food exporter, Brazil, in particular, has come under global scrutiny for practices deemed unsustainable—such as deforestation, excessive use of agrochemicals, and socio-environmental conflicts—despite its agricultural sector being a vital contributor to global food security. To provide policymakers with a robust monitoring tool, this study develops a nonlinear regression model that quantifies rural sustainability across economic, social, and environmental dimensions. We selected seven indicators—gross value added, average rural income, life expectancy, schooling years, preservation-area deficit, legal-reserve deficit, and water-scarcity deficit—to compute individual sub-indexes. These are combined into a composite rural sustainability index and applied to data from 141 municipalities in Mato Grosso. The results demonstrate that only municipalities achieving high and balanced scores in all three pillars can be deemed sustainable. Our framework contributes to the growing body of triple-index methodologies by offering a replicable, statistically robust tool tailored to agrarian contexts. It provides actionable insights for regional decision-makers aiming to balance productivity, environmental preservation, and social well-being in agricultural frontier regions.

Keywords: sustainability index; agrarian expansion; agricultural sustainability; nonlinear regression model; Mato Grosso

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1. Introduction

Since the 1970s, Brazilian agribusiness has undergone a remarkable transformation driven by technological advancements, policy support, and research investments. In collaboration with private entrepreneurship, public institutions have played a crucial role in adapting tropical agriculture to Brazil's diverse ecosystems. This enabled agricultural expansion into previously undeveloped regions of the Center–West, particularly Mato Grosso (MT) and Goiás (GO) [1–4]. Mato Grosso, in particular, plays a critical role, being the largest producer of key commodities—soybeans, corn, and cotton—and hosting the country's largest cattle herd [5].

Implementing large-scale mechanization, soil-management techniques, and high-yielding crop varieties has significantly enhanced agricultural productivity. Productivity in yield per hectare has increased by about 3 percent per year over the past four decades, and exports have more than quintupled since 1990, establishing Brazil as a leading global food supplier [1–4]. Significant environmental and social concerns have emerged against this backdrop of rapid agricultural expansion, including deforestation, excessive pesticide use, biodiversity loss, and land conflicts involving indigenous communities [6]. Balancing economic growth with environmental conservation and social equity is critical for ensuring long-term sustainability [6].

The recent literature underscores the growing need for multidimensional approaches to assess agricultural sustainability, particularly in regions undergoing rapid agrarian transformation. Jatav and Naik (2023) applied a Pressure–State–Response (PSR) model to evaluate agricultural sustainability across India's agro-climatic zones, highlighting how regional disparities influence sustainability rankings [7]. Similarly, Song et al. (2024) employed emergy analysis and logarithmic mean division index decomposition in China's Liaohe River Basin to illustrate the impact of socioeconomic structure on sustainability performance [8]. In South America, Soldi et al. (2019) applied the FAO's SAFA framework to assess heterogeneous farming systems in Paraguay, revealing how governance and environmental integrity vary dramatically between agribusiness and traditional systems [9]. From a methodological standpoint, Fallah-Alipour et al. (2018) combined fuzzy AHP and composite indexing to map sustainability risks in Iran's agricultural sector, offering visual tools that improve decision-making granularity [10]. Likewise, Suresh et al. (2022) developed a macro-level index-based sustainability model for Indian agriculture using the DPSIR framework, emphasizing trade-offs between environmental and economic indicators [11]. In Brazil, Machado et al. (2015, 2017) [12,13] and Gilio and Dias de Morais (2016) [14] conducted critical studies assessing sugarcane expansion's socioeconomic and spatial impacts, using panel data and sustainability indicators to evaluate local development outcomes. Their work emphasizes the value of spatially sensitive indicators and composite approaches within rapidly evolving agricultural contexts. De Olde et al. (2017) added a critical lens by highlighting disagreements among experts regarding indicator selection, stressing the need for transparent and participatory processes in sustainability assessments [15]. These studies demonstrate that while varied frameworks exist, most either lack spatial precision or are context-bound. Our proposed model addresses these limitations by offering a replicable, municipal-level sustainability index tailored to agrarian frontier regions like Mato Grosso, integrating methodological rigor with regional specificity.

This study proposes a theoretical model to calculate a sustainability index based on seven key indicators, enabling a comprehensive assessment of sustainable agricultural development across Mato Grosso. The guiding question of this research is: Can a composite index—grounded in nonlinear regression and seven key indicators—effectively evaluate sustainable rural development at the municipal level in agrarian frontier regions like Mato Grosso?

Mato Grosso is particularly compelling for this research due to its socioeconomic and environmental complexity. Located in the Central–West region of Brazil (8–19° S, 51–62° W), MT is the third-largest state in Brazil, covering 90.3 million ha [16]. Its territory originally encompassed three major biomes: the Amazon forest (56.7%), the Cerrado savannah (37.4%), and the Pantanal wetlands (5.9%) [16]. Its unique geographic location, abundant watersheds, and diverse climatic, geological, edaphic, and phytoecological features contribute to an impressive mosaic of ecosystems critical for biodiversity and environmental sustainability [17].

MT's agricultural prominence is reflected in its 2020 GDP of USD 34.6 billion—12th among Brazilian states—with agriculture contributing 25.8 percent of the gross value added [IBGE]. Although MT is considered an agrarian state, only 18 percent of its population live in remote rural areas; 82 percent reside in small urban centers that have emerged over the past four decades [18]. In 2021, MT ranked 11th on the Municipal Human Development Index of Federation Units (IDHM) [19].

By offering a replicable, data-driven tool, our framework fills a methodological gap and provides actionable insights for policymakers and stakeholders aiming to foster truly sustainable agrarian development.

2. Materials and Methods

2.1. Indicators, Indexes, and Data Sources

We selected seven indicators to capture the three dimensions of rural sustainability, each aligned with key Sustainable Development Goals (SDGs 1, 2, 3, 4, 6, 8, 15) and available for all 141 municipalities from reputable public sources (Table 1). To characterize agricultural sustainability, we formed three sub-indices (Table 2):

Economic index:

- GV: Gross value added by agricultural activities (kUSD municipality^{-1} year^{-1}).
- AI: Adjusted average annual income of rural establishments (kUSD establishment^{-1} year^{-1}).

Social index:

- LE: Life expectancy (years).
- SY: School attendance (years), based on a 0–20 year cycle.

Environmental index:

- rPPA: Relative permanent preservation area deficit (m^2 m^{-2}).
- rLR: Relative legal reserve area deficit (m^2 m^{-2}).
- rWS: Relative water scarcity (m^3 m^{-3}).

Table 1. Description and justification of the seven indicators used in our model.

Abbreviation	Category	Description	Justification
GV	Economic	Gross value added by agriculture activities (kUSD municipality^{-1} year^{-1})	Reflects overall agricultural output and economic viability at the municipal level (SDG 8).
AI	Economic	Adjusted average annual income of rural establishments (kUSD establishment^{-1} year^{-1})	Captures establishment-level prosperity and income distribution, indicating local welfare (SDG 1, 2).
LE	Social	Life expectancy (years)	Serves as a proxy for community health and social well-being, reflecting healthcare access and living conditions (SDG 3).
SY	Social	School attendance (years)	Measures human capital through educational attainment, linked to social equity and future productivity (SDG 4).
rPPA	Environmental	Relative permanent preservation area deficit (m^2 m^{-2})	Quantifies shortfalls in legally mandated riparian and hill-slope buffer zones under Brazil's forest code (Law 12,651/2012), critical for maintaining water regulation, soil stabilization, and biodiversity (SDG 15).

Table 1. *Cont.*

Abbreviation	Category	Description	Justification
rLR	Environmental	Relative legal reservation area deficit ($m^2\ m^{-2}$)	Measures deficits in required on-farm forest reserves under Law 12,651/2012. Compliance with these reserves is essential for legal conformity and sustaining ecosystem services—water regulation, soil protection, and biodiversity—that underpin agricultural productivity and rural livelihoods (SDG 15).
rWS	Environmental	Relative water scarcity ($m^3\ m^{-3}$)	Calculates the deficit between municipal water demand and Q95 surface-water availability. Although irrigation is uncommon in Mato Grosso, deforestation-driven shifts in rainfall patterns can reduce soil moisture and yields. Empirical data show natural water coverage in the state declined by 32.2 percent between 1985 and 2001-during rapid frontier expansion-before stabilizing alongside productivity gains. Early studies also warn that Amazon deforestation may disrupt moisture transport to the Center–West, reducing rainfall [20,21].

Note: All indicators were normalized to the [0, 1] range prior to index calculation (see Section 2.3).

Table 2. Description of the economic, social, and environmental indexes.

Economic index	Range	Description
E_1	$0 \leq E_1 \leq 1$	Referring to the gross value added by agricultural activities in the municipality.
E_2	$0 \leq E_2 \leq 1$	Referring to the adjusted average annual income of rural establishments located in the municipality.
Social index	Range	Description
S_1	$0 \leq S_1 \leq 1$	Referring to the life expectancy in the municipality.
S_2	$0 \leq S_2 \leq 1$	Referring to the educational level in the municipality.
Environmental index	Range	Description
A_1	$0 \leq A_1 \leq 1$	Referring to the relative permanent preservation area deficit.
A_2	$0 \leq A_2 \leq 1$	Referring to the relative legal reserve area deficit.
A_3	$0 \leq A_3 \leq 1$	Referring to the relative water scarcity.

These indicators collectively ensure a comprehensive, data-driven assessment of economic viability, social welfare, and environmental integrity, tailored to the agrarian frontier context of Mato Grosso. All data were extracted from official, governmental, or scientific databases with public access (Table 3). Monetary values in Brazilian Reals (BRL) were converted to USD using the official foreign exchange rates published by the Brazilian Central Bank (BACEN), available on <https://www.bcb.gov.br/estabilidadefinanceira/historicocotacoes> (accessed on 10 October 2024 (Table 4)).

Table 3. Public databases used and corresponding links to access.

Variable	Description	Publisher	Link
GV	Extracted from Table 5938, including the gross domestic product at current prices, taxes, net of subsidies on products at current prices, and gross value added at current prices, total and by economic activity, and respective shares—Reference (base year) 2010. Data referring to the year 2018.	Brazilian Institute of Geography and Statistics (IBGE).	https://sidra.ibge.gov.br/tabela/5938#notas-tabela (accessed on 18 January 2022)
AI	Extracted from Table 6902, including the number of agricultural establishments that obtained revenue or other producer income and value of revenue or income obtained by agricultural establishments, by typology, establishment income, and other producer income and total area groups. Data referring to the year 2017 (last agricultural census).	Brazilian Institute of Geography and Statistics (IBGE).	https://sidra.ibge.gov.br/Tabela/6902 (accessed on 5 January 2022)
LE	Extracted from the Human Development Atlas Brazil Data referring to the year 2018.	Atlas Brazil is the product of a partnership between the United Nations Development Program (UNDP), the Institute for Applied Economic Research (IPEA), and the João Pinheiro Foundation (FJP).	http://www.atlasbrasil.org.br/acervo/biblioteca (accessed on 12 January 2022)
SY	Extracted from Table 6849, showing the number of agricultural establishments by typology, use of limestone or other soil pH correctors, farmer's sex, farmer's age class, farmer's condition about land, and farmer's education. Data referring to year 2017 (last agricultural census).	Brazilian Institute of Geography and Statistics (IBGE).	https://sidra.ibge.gov.br/tabela/6849 (accessed on 5 January 2022)
rPPA rLR	Land network study. Title: Nota técnica: Malha fundiária do Brasil, v.1812. In: Atlas—A Geografia da Agropecuária Brasileira, 2018.	Imaflora, ESALQ/USP's GeoLab, the Royal In-stitute of Technology (KTH, Sweden), and the São Paulo Federal In-stitute for Education, Science and Technolo-gy.	https://atlasagropecuario.imaflora.org/ (accessed on 5 January 2022)
rWA	Q95 flow and consumptive uses Data referring to the year 2021.	Agência Nacional de Águas e Saneamento Básico.	https://metadados.snirh.gov.br/geonetwork/srv/eng/catalog.search#/metadata/7ac42372-3605-44a4-bae4-4dee7af1a2f8 (accessed on 12 January 2022) https://metadados.snirh.gov.br/geonetwork/srv/eng/catalog.search#/metadata/5146c9ec-5589-4af1-bd64-d34848f484fd (accessed on 12 January 2022)

Table 4. Exchange rates used to convert monetary values expressed in Brazilian Reals (BRL) to USD.

Variable	Description	Year	Average Annual Forex Rate
GV	Gross value added by agriculture activities	2018	3.65578 BRL/1.00 USD
AI	Adjusted average annual income of rural establishments	2017	3.19254 BRL/1.00 USD

2.2. The Theoretical Model and Composite Index

To transform each normalized indicator x_i ($0 \leq x_i \leq 1$) into a sub-index Y_i ($0 \leq Y_i \leq 1$), we employ the following nonlinear regression model:

$$Y_i = 1 - \frac{1 - x_i^{\alpha}}{1 + \left(\frac{x_i}{x_m}\right)^{2.\beta.(x_m + x_i)}} \quad (1)$$

where x_i refers to the normalized value of indicator i, x_m = 0.5 is the median of the normalized distribution, and α and β are the model's empirical parameters determined through nonlinear regression analysis using the software Table Curve 2D, version 5.0 (Figure 1, Table 5).

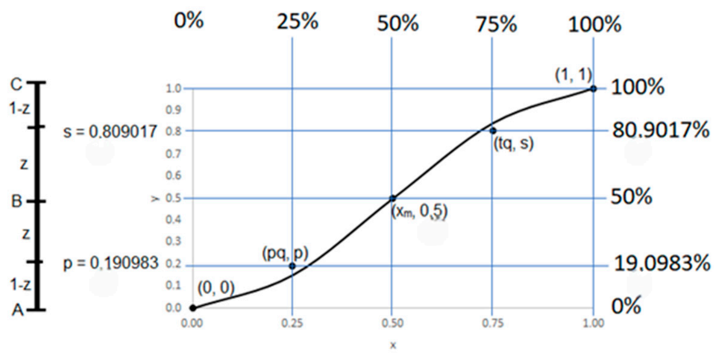

Figure 1. Schematic illustration of the theoretical model (solid line).

Rationale for this formulation:

- At x_i = 0, the numerator 1 − 0α = 1 and the denominator 1 + 0 . . . = 1, yielding Y_i = 0.
- At x_i = 1, the numerator 1 − 1α = 0, yielding Y_i = 1.

This ensures that Y_i ranges exactly between 0 and 1.
Golden ratio anchoring:

- We define two key points: the normalized distribution's first quartile pq and third quartile tq. Their corresponding target sub-index values are p = 0.190983 and s = 0.809017, derived from the golden ratio $\phi = \frac{1+\sqrt{5}}{2}$.
- The exponent 2β (x_m + x_i) adjusts the curve's steepness asymmetrically around the median, ensuring the model passes through (pq, p) and (tq, s).

Symmetrical S-shape:

- For $x_i < x_m$, the denominator term remains relatively small, producing a flatter slope near zero.
- For $x_i < x_m$, the term grows rapidly, steepening the curve near the median. This yields the characteristic S-shape with inflection at x_m.

Once each x_i is mapped to Y_i, we compute the three sub-indexes:

Table 5. Description and physical interpretation of the theoretical model (Equation (1)) to characterize agriculture's economic, social, and environmental sustainability in the state of Mato Grosso.

Sustainability Indicator	Sustainability Index	Interpretation and Description
x_i	$Y_i = 1 - \frac{1 - x_i^{\alpha}}{1 + \left(\frac{x_i}{x_m}\right)^{2.\beta.(x_m + x_i)}}$	Equation (1): xi represents the indicators' relative average value ($0 \leq x_i \leq 1$), x_m the indicators' median value, and α and β the empirical parameters (curve shape factors) of the model determined through nonlinear regression analysis using Table Curve 2D Software.
$x_i = 0$	$Y_i = 0$	Lower limit: the value of the sustainability index is null when the value of the sustainability indicator is null (theoretical minimum value). Point coordinate: (0, 0) (Figure 1).
$x_i = pq$	$Y_i = 1 - \frac{1 - x_{pq}^{\alpha}}{1 + \left(\frac{x_{pq}}{x_m}\right)^{2.\beta.(x_m + x_{pq})}}$	Limit referring to the first quartile: the index value is approximately 0.190983 (p) (corresponding to the p point) when the indicator value is the first quartile. Point coordinate: (pq, p) (Figure 1).
$x_i = x_m$	$Y_i = 1 - \frac{1 - x_m^{\alpha}}{2}$	Limit referring to the median: the index value is approximately 0.5 when the indicator value is the median: lim (Y_i) = 0.5 for $\alpha \rightarrow \infty$ Point coordinate (xm = 0.5) (Figure 1).
$x_i = tq$	$Y_i = 1 - \frac{1 - x_{tq}^{\alpha}}{1 + \left(\frac{x_{tq}}{x_m}\right)^{2.\beta.(x_m + x_{tq})}}$	Limit referring to the third quartile: the value of the index is approximately 0.809017 (s) (corresponding to the pos) when the indicator's value is the third quartile. Point coordinate: (tq, s) (Figure 1).
$x_i = 1$	$Y_i = 1$	Upper limit: the index value is unitary when the indicator value is unitary (theoretical maximum value). Point coordinate: (1, 1) (Figure 1).
First derivative		
$\frac{dY_i}{dx_i} = \frac{-\alpha x_i^{\alpha-1}.\left[1+\left(\frac{x_i}{x_m}\right)^{2.\beta.(x_m+x_i)}\right] + \frac{2.\beta.\left(1-x_i^{\alpha}\right)}{x_m}.\ln\left(\frac{x_i}{x_m}\right).\left[\left(\frac{x_i}{x_m}\right)^{2.\beta.(x_m+x_i)}\right]}{\left[1+\left(\frac{x_i}{x_m}\right)^{2.\beta.(x_m+x_i)}\right]^2}$		Variation in the index in relation to the indicator's point value.

Based on the five coordinate points shown in Figure 1 and Table 5, we calculated the values for each of the seven indicators, formed the three indexes, and classified the results into four classes (Table 6).

Table 6. Classification into four classes, based on the lower and upper limits, according to the minimum, first quartile, median, third quartile, and maximum values of the seven indicators detailed in Table S1.

Classes	Description	Lower Limit	Upper Limit
1	Upper	Third quartile (suffix tq)	Maximum (suffix x)
2	Upper average	Median (suffix m)	Third quartile (suffix tq)
3	Lower average	First quartile (suffix pq)	Median (suffix m)
4	Lower	Minimum (suffix n)	First quartile (suffix pq)

2.3. Calculation Methodology

We calculated the indicator GV_i representing the average annual gross value added by agricultural activities in the state's i-th municipality (i = 1 to 141) as follows:

$$GV_i = \frac{1}{ni}\sum_{j=1}^{ni} GVi, j \quad (2)$$

where $GV_{i,j}$ refers to the annual gross value added by the j-th rural establishment in the i-th municipality in USD and n_i to the number of rural establishments in the i-th municipality.

We determined the index representing the annual gross value added by agricultural activities ($E1_i$) referring to the i-th municipality, using Equation (1) with xi as follows:

$$x_i = \frac{GV_i}{GV_x} \quad (3)$$

where GV_x refers to the maximum annual gross value added by agricultural activities in USD achieved by a rural establishment located in the municipality (x_i = 1), while x_i ($0 \leq x_i \leq 1$) refers to the relative average gross value added by agricultural activities in this municipality. Figure 2 shows the geospatial distribution of the results.

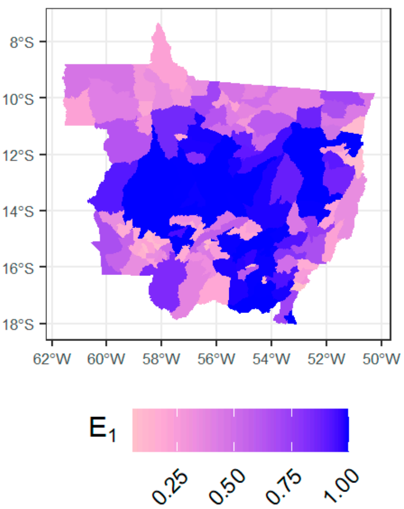

Figure 2. Geospatial distribution of the index E1, representing the annual gross value added by agricultural activities in the state.

We calculated the rural economic development index for each municipality (IEi) as follows:

$$IEi = \sqrt{E1i.E2i} \quad (4)$$

where $E1_i$ refers to the index representing the gross value added from agriculture, and $E2_i$ to the index representing the average adjusted income of the state's i-th municipality.

We then applied the same methodology to determine the remaining indicators and sub-indices that form our model's social and environmental components, namely the rural social development index IS_i:

$$IS_i = \sqrt{S1_i.S2_i} \quad (5)$$

where $S1_i$ refers to the index representing life expectancy, and $S2_i$ to the index representing the years of education, considering a school cycle from 0 (minimum value) to 20 years (maximum value) of the state's i-th municipality and the rural environmental development index IAi:

$$IA_i = \sqrt[3]{A1_i.A2_i.A3_i} \quad (6)$$

where $A1_i$ refers to the index representing the relative permanent preservation area deficit, $A2_i$ to the index representing the relative legal reserve area deficit, and $A3_i$ to the index representing the water scarcity in the state's i-th municipality.

We determined the rural sustainable development index ISDi as follows:

$$ISD_i = \sqrt[3]{IE_i.IS_i.IA_i} \quad (7)$$

where IE_i refers to the economic development index, IS_i to the social development index, and IA_i to the environmental development index of the state's i-th municipality.

We have consolidated the detailed results in the Supplementary Materials. Table S3 shows the indicators' reference values (minimum, first quartile, median, average, third quartile, and maximum). Tables S4–S6 offer the base values referring to the three indexes and seven indicators related to the 141 municipalities to estimate the empirical parameters. The statistics referring to the sustainable development indexes are presented in Tables S7 and S8. The ranking of the 141 municipalities can be found in the Supplementary Materials (Tables S9–S12).

3. Results and Discussion

An isolated look at the economic index shows that the municipalities located in the center, a region with favorable edaphoclimatic conditions for agriculture, present the best results (Figure 3). This is not surprising considering the importance of agriculture in this state. The five municipalities with the highest economic development index are in descending order 'Primavera do Leste', 'Sapezal', 'Campo Novo do Parecis', 'Sorriso', and 'Nova Mutum'. Agriculture is highly industrialized, capital-intensive, and practiced on a large scale in all these municipalities.

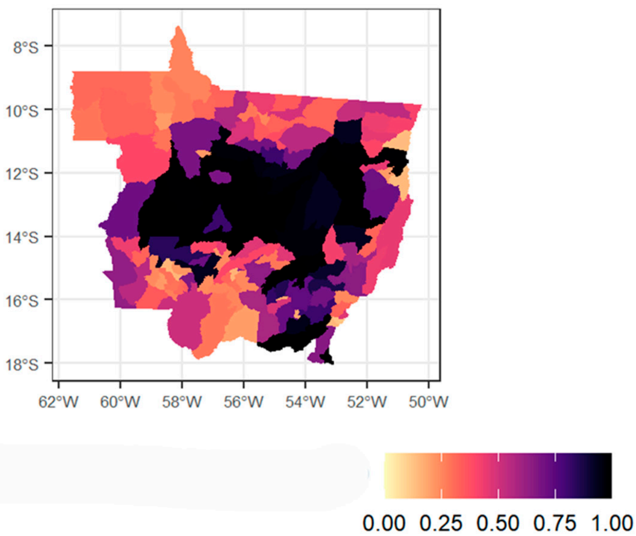

Figure 3. Map of MT illustrating the economic index (IE) results based on the values presented in Tables S9–S12.

With USD 7200.77 for each of the 111 agricultural establishments located in an area of 13,598 km^2, 'Sapezal' has the highest average income per establishment. 'Sapezal' is the state's most important cotton producer, followed by 'Campo Verde' and 'Campo Novo do Parecis'. Cotton is the most valuable crop among the three primary commercial commodities, cotton, soybeans, and corn. In 2020, 'Sapezal' generated 35.5% of its revenue from soybeans and 54.4% from cotton [22].

However, we observed that the number of rural establishments in each municipality impacts the results. Comparing 'Sapezal' and 'Sorriso', we remarked that the total income generated in 'Sorriso' exceeds that of 'Sapezal' by 15% despite 'Sorriso' having a minor territorial extension. However, the average income per rural establishment dropped to USD 1142.49 as 'Sorriso' counts 807 establishments in an area of 9346 km^2.

Recently, corn ethanol plants were installed in 'Sorriso' and 'Nova Mutum', adding value to the production chain of these municipalities and the nearby regions [23].

In descending order, the five municipalities with the lowest economic development index are 'Ponte Branca', 'Luciara', 'Novo Santo Antônio', 'Reserva do Cabaçal', and 'Araguainha'. All five municipalities have a small territorial area and a low population density, which can inhibit successful economic development.

In descending order, the top five municipalities regarding the social index are 'Santa Rita do Trivelato', 'Primavera do Leste', 'Araguainha', 'Sapezal', and 'Sorriso' (Figure 4). Again, we observed a strong lead of the municipalities with agrarian predominance, except for 'Araguainha', occupied in the 1940s by mining activities [22]. Despite 'Araguainha' being the smallest municipality in MT with a poor economic performance, its life expectancy and schooling results were outstanding.

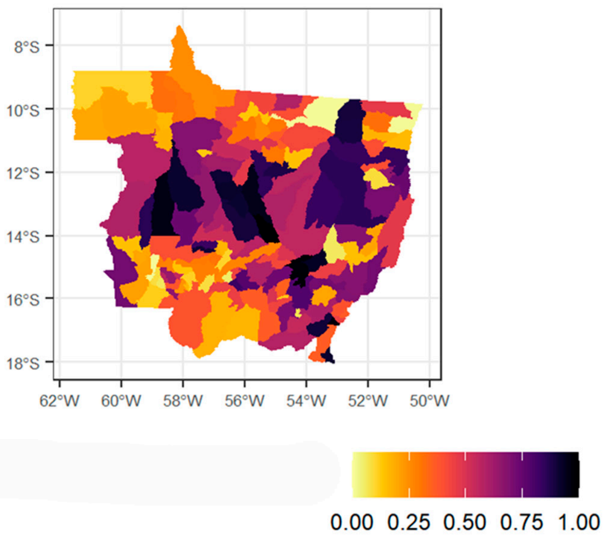

Figure 4. Map of MT illustrating the results of the social index (IS) based on the values presented in Tables S9–S12.

Our model results indicate lower social indexes in the extreme north of the state, in the municipalities with borders to the states Pará, Amazonas, Rondônia, and Tocantins. Most of these remote areas are regions of agricultural expansion or regions where mineral exploitation is the principal economic activity.

'Vale de São Domingos', 'Peixoto de Azevedo', 'Santa Terezinha', 'Jangada', and 'Campinápolis' are the municipalities with the lowest social index. Their life expectancy and educational levels are far below the state's average of 74.2 years [24].

'Peixoto de Azevedo' and 'Santa Terezinha', located in the north of the state, have, with 70 years, the lowest life expectancy [24]. 'Peixoto de Azevedo' is a region where socio-environmental conflicts are widespread. Although agriculture and livestock have increased in the municipality, mining remains one of the main economic activities [25].

Life expectancy tends to be lower in regions with extensive mineral exploration, mainly due to environmental pollution caused by using mercury to extract precious minerals, high criminality, and land disputes between land grabbers, settlers, indigenous peoples, and farmers [22,25–29].

The negative socioeconomic impacts related to a high economic dependency on logging, and mineral exploitation, often still practiced illegally, are also reflected in the educational level. The number of citizens who never attended school is alarming in regions with mineral extraction as their main economic activity. Municipalities with high primary illiteracy are 'Poconé', 'Cáceres', 'Colniza', 'Peixoto de Azevedo', 'Confresa', and 'Juína' [30,31].

Our results align with the study Social Progress Index in the Amazon Region, which evidenced that deforestation, land grabbing, or illicit mining activity leads to poverty, violence, health issues, and poor social progress [30,31].

On the contrary, primary illiteracy is low in municipalities where modern agriculture is the main economic activity. A positive example is Lucas do Rio Verde. With approximately 70 thousand inhabitants, the municipality has 17 modernly equipped public school units. Two units outside the city are attended by rural students living in remote areas [22,32].

Due to the vast territorial extension of these agricultural municipalities, farmers often unite to contribute with donations of buses and construction materials to build schools in rural areas, thus helping to reduce school dropouts. In Sorriso, farmers also embraced the idea of building a new hospital in the city [22].

Figure 5 indicates that municipalities in the extreme northwest of the state that are not very explored yet, such as 'Aripuanã' and 'Colniza' and municipalities localized in the state's primary agriculture regions, show the highest environmental indexes. At first glance, this seems paradoxical, as intensive agriculture is often associated with deforestation and environmental pollution through the heavy use of pesticides and fertilizers. In addition, 'Colniza' and 'Aripuanã' presented the highest deforestation rates in the state in recent years [16].

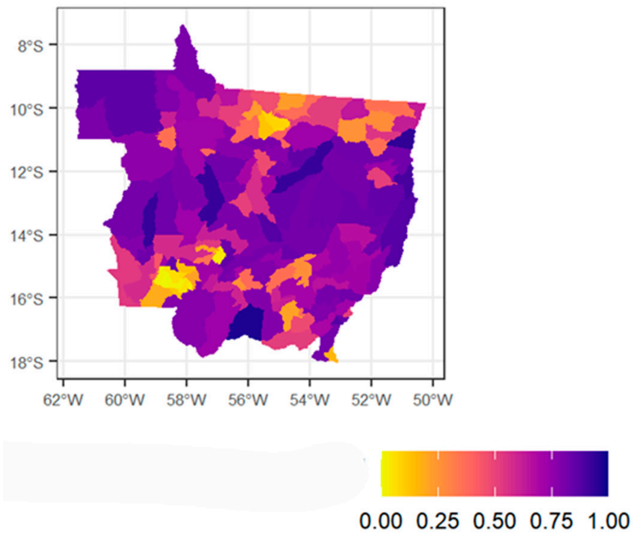

Figure 5. Map of MT illustrating the results of the environmental index (IA) based on the values presented in Tables S9–S12.

It is worth explaining two essential facts to understand the results better. First, we did not exclude in our model conservation areas or indigenous reserves from the calculation of the legal conservation requirements of a municipality, defined in Law 12,651 in terms of Permanent Preservation Area (PPA) and Legal Reserve (LR), as these requirements also apply to these protected territories.

In general, legally protected areas do not show environmental liabilities or a lack of freshwater availability and thus contribute positively to the municipalities' environmental index. Thus, municipalities that host large areas of protected territories, such as Sapezal, Campos de Júlio, Lucas do Rio Verde, and Feliz Natal, benefit from the park's compliance, even if some farms currently do not fulfill the legal requirements.

The second fact is related to the changes in the Brazilian forest code, which revoked the Forest Code of 1965 (Law 4771, 15 September 1965) and became Law 12,651 on 25 May 2012. The most significant changes affected the metrics of the main instruments for protecting native vegetation, namely the PPA and the LR.

At the time, there was great concern about these metrics, mainly because many rural producers, encouraged by the lack of monitoring and the low occurrence of fines, did not comply with the provisions of Law 4771 [33–37].

Pressures to change Law 4771/1965 arose mainly when additional legal instruments were established, namely the Environmental Crime Law (Law 9605, 12 February 1998) and the decree that regulates it (Decree 6514, 22 July 2008). These laws provided fines for farmers who did not comply with the forest code and required them to convert areas with existing environmental liabilities occupied by agricultural or livestock activities into forest areas [33–37]. In 2010, the environmental liability of PPA and LR in Brazil was estimated at around 85 million hectares [35].

In the state of São Paulo alone, compliance with the previous forest code would have generated an estimated cost of USD 8.4 billion, representing more than half of the income generated by agriculture in São Paulo in 2005. Thus, farming for many rural producers would have been unfeasible [35].

According to the new law, it is estimated that the area of environmental liability in PPA and LR on rural properties in Brazil has been reduced fourfold, resulting in an environmental debt of 21.2 million hectares [34–37].

The approval of the new forest code implied the amnesty of fines and other sanctions, such as the requirement of reforestation resulting from illegal deforestation before the enactment of Decree 6514/2008, affecting mainly the deforestation carried out during the rural expansion from the 1970s forward. Further, small properties with an area of less than four fiscal modules were excluded from the obligation to recover irregularly deforested areas [33].

Nevertheless, the new law generated greater expectations of implementation and compliance, as it strengthened several instruments of forestry policy that were previously regulated in decrees or resolutions of the National Council for the Environment (Conama) and normative instructions, among other legal forms [33].

In addition, compliance with the forest code is a precondition to obtaining loans from public or private credit institutions. As modern agriculture is capital intensive, it is in the interest of any producer to regulate eventual environmental liabilities within the deadline established by law.

This explains why regions with agricultural predominance in the state's center present higher environmental indexes than the municipalities of rural expansion in the northeast or north–center parts of the state or in areas where mineral extraction or logging are widespread.

High environmental indexes were also found in the municipalities embedded in the Pantanal, such as 'Barão do Melgaço', a municipality in the extreme south of the state, which presented the highest environmental index in the state. The municipality hosts three important ecological preservation areas: Sesc Pantanal, Encontro das Águas State Park, and the Baia dos Guató indigenous reserve.

Generally, the municipalities that belong to the Pantanal or are access routes for regional tourism present exemplary environmental indexes. However, the Pantanal biome recently faced significant environmental challenges, mainly due to extensive bushfires in the dry season. In 2020, the National Institute for Space Research (INPE) registered the highest bushfire rate since records began in 1990 [38].

'Indiavaí', 'Figueirópolis d'Oeste', 'São José dos Quatro Marcos', 'Curvelândia', 'Jauru', and 'Denise' present the lowest environmental indexes. Mineral exploration in these regions peaked in the 1980s, and the lack of legal regulation generated significant environmental liabilities. However, the extractive exploration of minerals, logging, and extensive livestock are still common in these municipalities. According to the Mineral Resources Research Company, erosion and alluviation caused by rudimentary and often illegal mining activities at the riversides are one of the main reasons for the siltation of watercourses in the municipalities of 'Figueirópolis d'Oeste', 'Indiavaí', 'São José dos Quatro Marcos', and 'Jauru'.

The situation is similar in the north of the state, where the extraction of wood and minerals and extensive livestock are the main drivers for the local economy, causing significant environmental damage [22,28,29].

Finally, the rural sustainable development index (IDS) aims to obtain a complete picture of rural sustainability as it unites all three dimensions of sustainability. In Figure 6, we detail the results of the 31 municipalities that achieved the highest IDS and their results obtained in each of the three sub-indexes composing it.

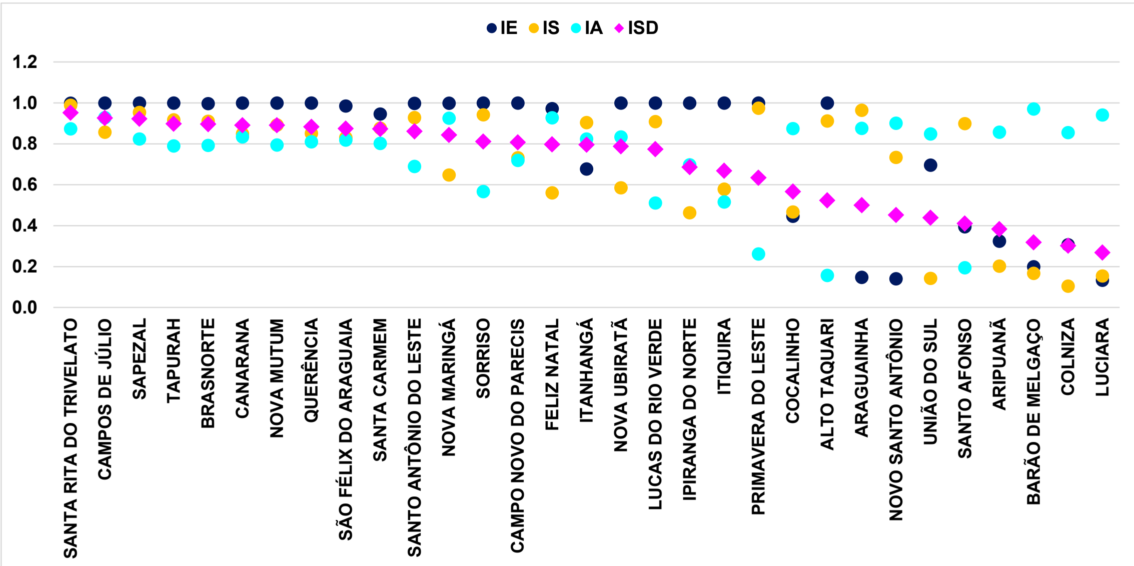

Figure 6. Descending ranking of the 31 municipalities with the highest indices achieved regarding sustainable rural development (ISD) and the results obtained in economic (IE), social (IS), and environmental (IA) sustainability.

The results evidence that to be considered a sustainable agricultural municipality, the municipality must show a high performance and balance all three pillars of sustainability, as is the case for the municipalities ranking within the top 10. All other municipalities show suboptimal performance in at least one index.

The leading municipality, 'Santa Rita do Trivelato', was colonized in 1977, i.e., during the Green Revolution by Colonizadora Trivelato, who acquired the area and sold land to farmers from the south of Brazil, attracted by new economic opportunities from agricultural activities, which is still the primary economic source of this municipality. The region is surrounded by several rivers and springs, including the Teles Pires River, the Verde River, the Beija Flor River, the Morocó River, and the Cuiabá River, guaranteeing freshwater availability throughout the year. Further, the region hosts two State Environmental Protection Areas, the APA Salto Magessi and APA Cabeceiras do Rio Cuiabá, contributing to the LR area of the municipality [22]. 'Sapezal' has a similar history. Here, the Maggi Group carried out the colonization proposal, selling land to southern settlers.

Other agricultural strongholds explored during the same time, such as 'Sorriso', 'Santo Antônio do Leste', 'Lucas do Rio Verde', 'Primavera do Leste', 'Campo Novo de Parecis', and 'Nova Ubiratã' show high economic indexes. However, they lack environmental performance, mainly due to LR deficits. At the same time, in 'Feliz Natal' and 'Nova Maringá', the economic growth has not yet been reflected in a solid social system, leaving life expectancy and the educational level below the values obtained by other agricultural strongholds in the neighborhood.

On the contrary, 'Luciara', located in the Xingu Valley, ranks second in the environmental index. However, the municipality occupies the penultimate place in the economic ranking as subsistence agriculture and semi-intensive livestock, which are the main economic base of this municipality, did not generate sufficient economic growth to provide a solid health and educational structure [22].

The five municipalities with the lowest sustainable rural development index, marked in yellow in Figure 7, are 'Figueirópolis d'Oeste', 'Indiavaí', 'Jauru', 'Vale de São Domingos', and 'Curvelândia'. These municipalities, located in the state's southwest, have a small territorial extension compared to other municipalities. 'Curvelândia' is the state's second-smallest municipality.

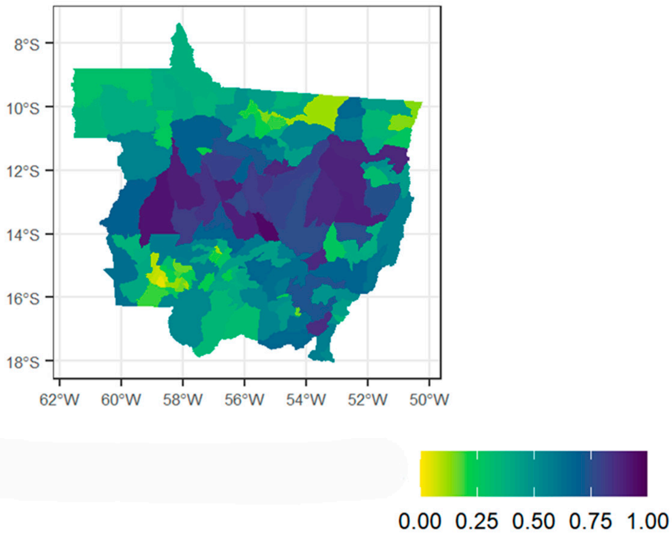

Figure 7. Map of MT illustrating the results of the sustainable rural development index (IDS) based on the values obtained from the theoretical model.

Subsistence agriculture and extensive livestock farming focused on dairy cattle are the main economic activities in 'Vale de São Domingos' and 'Curvelândia'. These municipalities were colonized by settlers coming from Minas Gerais and São Paulo, encouraged to find and explore precious metals [22]. 'Jauru', 'Indiavaí', and 'Figueirópolis d'Oeste' and part of 'Vale de São Domingos' are part of the Jauru domain, with considerable metallogenetic deposits of Cu, Zn, Pb, Zn, Ag, Ni, and Au [39]. The Federal Constitution of 1988 defined the subsoil and mineral assets in Brazilian territory as belonging to the Union, which can promote and grant mining titles to the exploration and use of mineral resources. This impacts a region's agricultural development, as the farmers demand stability and security, mainly because modern agriculture is capital-intensive.

3.1. Classification Patterns and Municipal Performance

We observe clear spatial patterns by classifying each sub-index into four quartile-based performance classes (Table 6). Class 1 ("upper") municipalities—those scoring above the third quartile—are concentrated in the state's central corridor, where intensive, mechanized agribusiness predominates. These 35 municipalities (e.g., Santa Rita do Trivelato, Campos de Júlio, Sapezal) combine high economic output (IE $\approx$ 0.99–1.00), strong social welfare (IS ≈ 0.85–0.99), and relatively low environmental deficits (IA ≈ 0.79–0.93), yielding composite ISD values ≥ 0.68 (Table S9).

Conversely, Class 4 (“lower”) municipalities—those below the first quartile—are predominantly in the southwestern frontier and northern mineral-exploration zones (e.g., Figueirópolis d’Oeste, Indiavaí, Jauru). Here, limited economic diversification (IE < 0.40) and social challenges (IS < 0.50) coincide with substantial environmental liabilities (IA < 0.80), resulting in ISD < 0.46 (Table S12). These contrasts underscore that economic growth alone does not guarantee social or environmental sustainability.

3.2. Comparison with Previous Studies

To validate the robustness of the proposed rural sustainability index (ISD), we conducted a comparative analysis with the Social Progress Index (SPI), a nationally recognized metric emphasizing social and basic human needs. This section explores divergences and correlations between the two frameworks, offering insights into how environmental and economic dimensions may skew sustainability classifications. Our findings resonate with the Imazon Social Progress Index (IPS) for the Brazilian Amazon, highlighting that municipalities with intensive resource extraction and high deforestation often exhibit poor social outcomes.

For example, frontier towns like Colniza and Aripuanã—flagged by Imazon as hotspots of illicit mining and deforestation—register deceptively high environmental subindexes (IA) in our model. This occurs because large indigenous reserves and conservation units count as “compliant” land, inflating IA and masking on-farm preservation deficits. This mirrors IPS’s caution that aggregated conservation metrics can obscure localized environmental liabilities. These findings suggest that environmental compliance, especially when tied to geographic protection rather than proactive conservation efforts, can disproportionately elevate a municipality’s sustainability rating, highlighting the importance of critically weighting such indicators within composite index models.

IPS’s emphasis on healthcare, education, and safety also aligns with our social subindex (IS) patterns. Municipalities with top IPS rankings—such as Lucas do Rio Verde and Primavera do Leste—consistently appear in Class 1 for IS (IS > 0.90), underscoring the strong link between agribusiness-driven revenues and investments in public services.

In contrast, towns identified by IPS for limited basic services—like Peixoto de Azevedo and Santa Terezinha—fall into Class 4 for IS (IS < 0.60), reflecting chronic gaps in healthcare, education, and infrastructure.

Case comparisons: Lucas do Rio Verde (IPS #6; IPS = 67.24): Excels on IPS’s Basic Needs (74.7) and Well-Being (71.2) dimensions and ranks Class 1 economically (IE = 1.00) and socially (IS = 0.91) in our model. However, it reaches only Class 3 environmentally (IA = 0.51), revealing substantial on-farm conservation deficits that IPS’s aggregate scores do not capture.

Peixoto de Azevedo (IPS #90; IPS ≈ 58.3): Shows moderate IPS Basic Needs (60.2) and Well-Being (58.3) scores but falls into Class 3 economically (IE = 0.57) and Class 4 socially (IS = 0.46) in our index. Its relatively high IA (0.72, Class 2) is driven by extensive protected areas rather than widespread on-farm compliance. Peixoto de Azevedo exemplifies how environmental compliance metrics can obscure persistent social and economic challenges with a composite rural sustainability index (ISD ≈ 0.49).

These comparisons demonstrate the complementary strengths of IPS and our rural sustainability index (ISD): IPS effectively diagnoses social well-being and basic needs. At the same time, our index integrates economic viability and environmental liabilities at the municipal level.

In addition to the comparison with the Imazon Social Progress Index (IPS), our findings resonate strongly with previous research on agrarian expansion in Brazil. Machado et al. (2015, 2017) demonstrated that sugarcane expansion was closely linked to local quality of life improvements, notably where rural infrastructure investments accompanied agricultural growth [12,13]. Similarly, Gilio and Dias de Morais (2016) found that municipalities hosting sugarcane ethanol plants in São Paulo State achieved significantly better socioeconomic outcomes in education, health, and infrastructure [14]. This dynamic is mirrored in Mato Grosso's leading agricultural municipalities, such as Lucas do Rio Verde and Sorriso, where modern, capital-intensive agriculture has supported higher social development indicators. However, both studies also caution that without strong governance mechanisms, environmental sustainability may lag behind economic and social gains—a pattern our results confirm in Mato Grosso, where high economic outputs do not always correspond to strong environmental compliance.

In the broader South American context, Soldi et al. (2019) analyzed sustainability outcomes in Paraguay's farming systems, highlighting stark governance differences between industrial agribusinesses and traditional farms [9]. Their findings underline how governance quality shapes environmental and social sustainability—a phenomenon paralleled in our study, where Mato Grosso's rural expansion zones, often characterized by weak institutional frameworks, exhibit lower social and environmental scores despite agricultural growth.

Moving to international comparisons, Jatav and Naik (2023) and Song et al. (2024) emphasize how regional disparities and sectoral dependencies in India and China can distort overall sustainability rankings, even where economic prosperity is strong [7,8]. We observe a similar dynamic in Mato Grosso: municipalities with booming extractive or agricultural industries often lag socially or environmentally. Fallah-Alipour et al. (2018) and Suresh et al. (2022) further demonstrate that composite sustainability indices must be carefully calibrated to reflect local realities [10,11], a principle we incorporated by employing a nonlinear regression model anchored at golden-ratio points to balance indicator weighting.

Taken together, these comparisons affirm both the strengths and limitations of agrarian-led development strategies. While modern agribusiness models can promote socioeconomic welfare, as Mato Grosso and other frontier regions demonstrated, achieving true sustainability requires deliberate efforts to bridge persistent gaps across economic, social, and environmental pillars. Our findings highlight that economic growth alone does not guarantee environmental stewardship or social equity, particularly in regions with uneven institutional support. Unlike previous frameworks, our rural sustainability index specifically captures these multidimensional asymmetries at the municipal scale through a nonlinear regression model anchored in local realities. These results underscore the critical importance of integrating regional socioeconomic structures into sustainability assessments—a gap our model is uniquely designed to address. By explicitly capturing these multidimensional dynamics, our approach offers a valuable tool for guiding more balanced and sustainable regional development strategies.

3.3. Integrating Complementary Metrics for Sustainable Agrarian Development

Given the complexity of sustainability challenges in agrarian frontier regions, no single composite index can fully capture all relevant dimensions. Whether employing our rural sustainability index, the Imazon Social Progress Index, or other frameworks, policymakers should integrate complementary metrics that jointly address economic, social, and environmental pillars. Combining targeted social indicators with broader sustainability models can guide more balanced development strategies, ensuring that agricultural growth supports long-term social equity and ecological resilience. Future efforts should continue to refine integrative approaches that enhance both the precision and the applicability of sustainability assessments across diverse territorial contexts.

4. Conclusions

This study introduces a novel rural sustainability index (ISD), integrating economic, social, and environmental dimensions through a unified triple-index framework. Applied across 141 municipalities in Mato Grosso, the model reveals that truly sustainable agrarian regions must achieve high and balanced scores across all three pillars. Although agribusiness strongholds (e.g., Santa Rita do Trivelato, Sapezal) excel economically, persistent disparities in social welfare and environmental stewardship underscore the need for holistic development policies.

Key contributions:

- A replicable nonlinear regression model anchored in the golden ratio, enabling standardized sub-index computation for diverse indicators.
- Explicit classification of municipal performance into four quartile-based classes, facilitating targeted diagnostics.
- Demonstration of how aggregated conservation metrics can mask local environmental liabilities, and how composite indices can reveal nuanced sustainability profiles.

Limitations:

- Data sources: Reliance on official databases (IBGE, Atlas Brasil, ANA) may introduce temporal mismatches and reporting biases, particularly for environmental indicators derived from remote-sensing and cadastral studies.
- Golden ratio assumption: Anchoring quartile sub-index values at golden-ratio points (p = 0.190983, s = 0.809017) provides balanced score distributions but may not reflect context-specific thresholds in other regions.
- Spatial aggregation: Using municipal averages can obscure intra-municipal heterogeneity, especially in large territories with mixed land uses.

Future research directions:

- Sensitivity analyses: Evaluate the robustness of ISD to alternative anchoring schemes (e.g., quartile means, stakeholder-defined benchmarks) and to varying weights across dimensions.
- Comparative applications: Apply the model in other agrarian frontier contexts (e.g., Cerrado states, the Amazon north) to assess transferability and to refine indicator selection.
- Fine-scale assessments: Integrate sub-municipal data (e.g., farm-level or community-level surveys) to capture heterogeneity and to validate municipal-scale findings.

This framework fills a methodological gap in triple-index sustainability assessments for agrarian regions. It offers policymakers and stakeholders a data-driven tool to diagnose imbalances, prioritize interventions, and monitor progress toward truly sustainable rural development.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su17115210/s1.

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Abbreviations

Ag	Silver
AHP	Analytic Hierarchy Process
ANA	Agência Nacional de Águas e Saneamento Básico (National Water and Sanitation Agency)
APA	Área de Proteção Ambiental (Environmental Protection Area)
Au	Gold
BACEN	Banco Central (do Brasil)
BRL	Brazilian Real
Cu	Copper
DPSIR	Driving Force-Pressure-State-Impact-Response
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GO	Goiás
GPP	Grupo de Políticas Públicas (Public Policy Group)
ha	Hectare
IBGE	Instituto Brasileiro de Geografia e Estatística
IDHM	Human Development Index of Federation Units (IDHM)
INPE	Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research)
kUSD	thousand US Dollar
LR	Legal Reserve
MT	Mato Grosso
Ni	Nickel
Pb	Lead
PPA	Permanent Preservation Area
PSR	Pressure–State–Response
SAFA	Sustainability Assessment of Food and Agriculture systems
SDG	Sustainable Development Goal
SPI	Social Progress Index
USD	US Dollar
USP	Universidade de São Paulo
Zn	Zinc

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