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Aligning rural credit with sustainable practices: environmental indicators for agricultural policies

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This study examines the interface between rural credit policies and environmental sustainability objectives in Brazil, focusing on the 2023/2024 Harvest Plan and the 2024–2027 Pluriannual Plan (PPA). The analysis reveals that, despite normative advances, the integration of credit incentives with environmental performance indicators remains limited by operational gaps, regional concentration of resources, and deficiencies in monitoring systems. We argue that the use of the ratio between Total Factor Productivity (TFP) and Greenhouse Gas (GHG) Emissions as a sustainability metric is promising but requires methodological refinements and greater transparency. Our proposals include the official recognition of certified sustainable agricultural practices, smart territorial prioritization based on geospatial criteria, and the enhancement of territorialized Monitoring, Reporting, and Verification (MRV) systems. To operationalize credit targeting, we developed a Territorial Priority Index based on the normalization and combination of three variables: emissions-adjusted TFP, area of degraded pastureland, and a reduced history of sustainable credit.

KEYWORDS
agricultural policy, Brazil, ecological transition, environmental indicators, rural credit, sustainability, Territorial Priority Index

1 Introduction

The development of agricultural public policies aligned with socio-environmental transformations constitutes one of the major challenges for the contemporary state. In Brazil, where agribusiness accounts for approximately 27% of the national GDP and holds a prominent position in the international trade of commodities, this task assumes fundamental strategic dimensions. The Agricultural and Livestock Plan (Plano Agrícola e Pecuário - PAP), known as the "Harvest Plan" (Plano Safra), emerges as a central instrument for directing rural credit, insurance, subsidies, and innovation incentives, with direct impacts on production systems (Brasil, 2023a). The allocation of credit can be a decisive factor in steering the transition towards more sustainable production practices, representing a powerful mechanism for environmental governance.

The Brazilian agricultural sector faces a dual challenge: to increase production to meet domestic and global demands while simultaneously reducing its environmental impact. Official data from the Brazilian Government reveals that the sector is responsible for 27% of the country's gross emissions. The beef production chain accounts for 78% of the sector's emissions, predominantly from enteric methane (CH_4), a gas with a global warming potential 21 times greater than carbon dioxide (CO_2) (Brasil, 2024b).

Growing social and environmental pressure has forced a redesign of public policies, incorporating sustainability as a structural pillar. The Low-Carbon Agriculture Plan (Plano ABC) and its inclusion in rural credit lines exemplify this shift (MAPA, 2021). Launched in 2010 and updated as the ABC + Plan for the 2020–2030 period, this initiative represents the main strategy for sectoral climate policy, with ambitious targets to incorporate over 72 million hectares into sustainable systems and reduce more than 1 billion tons of CO_2 equivalent (Brasil, 2022).

Aiming to better guide the territorial allocation of financial resources for sustainability, this study proposes a Territorial Priority Index (TPI). The index combines three strategic variables: (i) the historical allocation of sustainable rural credit to states, (ii) the extent of degraded pastures as a proxy for environmental vulnerability, and (iii) Total Factor Productivity (TFP) as a measure of production efficiency. The normalization and weighting of these variables allow for the identification of regions with high potential for positive impact through the intensification of sustainable investments, reconciling criteria of equity, efficiency, and political opportunity.

This article adopts an applied research approach to critically assess how agricultural environmental indicators can guide public rural credit policies in Brazil. Drawing from official data sources and a custom-built composite index, the study analyzes the alignment between sustainability metrics and the geographic allocation of agricultural financing. The methodology includes the construction of a Territorial Priority Index (TPI), integrating credit access, pasture degradation, and Total Factor Productivity (TFP) into a normalized and replicable framework. The empirical application focuses on the 2023/2024 Harvest Plan (Brasil, 2023a) and its alignment with the goals of the 2024–2027 Pluriannual Plan (Brasil, 2024a). Based on this analysis, the paper offers policy recommendations to improve the integration between rural credit and sustainability, enhancing the sector's competitiveness in line with national and global environmental commitments.

2 Background

The literature on agricultural policies and environmental sustainability has evolved significantly in recent decades, providing important contributions to understanding the mechanisms for incentivizing the adoption of sustainable practices. Internationally, experiences such as the Environmental Quality Incentives Program (EQIP) in the United States and the Common Agricultural Policy (CAP) in the European Union offer valuable insights into the integration of rural credit and environmental targets (OECD, 2022).

In the Brazilian context, studies on the ABC Plan reveal significant advances, but also persistent challenges. Gianetti and Ferreira Filho (2021) demonstrated strong disparities in resource allocation, with 65% of financing concentrated in the Central-West and Southeast regions and 98% allocated to just four of the planned technologies. This regional and technical concentration limits the program's mitigation potential, diverting resources from areas with a greater need for intervention.

Spatial econometrics emerges as a promising tool for smart territorial prioritization. Bolfe et al. (2024) used geospatial databases to identify areas with degraded pastures that have high potential for conversion to agriculture or livestock intensification. Their study identified approximately 28 million hectares of planted pastures in an advanced stage of degradation with potential for conversion to cropland, a figure that approaches the initial targets of the ABC + Plan.

The discussion on sustainability indicators is also advancing in the specialized literature. Bragagnolo and Tateishi (2022) developed an environmentally sensitive measure of TFP, incorporating the negative externalities of GHG emissions. Their findings corroborate the usefulness of the TFP/emissions ratio as a proxy metric for environmental efficiency, although they acknowledge methodological limitations.

International studies on Brazilian policy highlight bureaucratic and implementation challenges. He (2022) from Peking University identified administrative difficulties as critical barriers, including the complexity of the financing application processes and the requirement for a validated Rural Environmental Registry (Cadastro Ambiental Rural - CAR) — a condition that excludes approximately 94% of producers, given that, "by September 2025, approximately 485,000 registrations had been validated, corresponding to just over 6% of the national database" (Lopes, 2025).

The literature also points to the need for robust Monitoring, Reporting, and Verification (MRV) systems. Laborde et al. (2020) argues that the lack of public and standardized measurement tools has hindered external and independent evaluation of the ABC + Plan, limiting accountability and institutional learning.

2.1 Sustainable agricultural policy context

Brazil has a suite of programs focused on sustainability, with the ABC + Plan (2020–2030) being the primary agricultural strategy. Its targets, established by MAPA Ordinance No. 472/2022 (Brasil, 2022), include the restoration of 30 million hectares of degraded pastures, the adoption of 12.5 million hectares of no-till grain farming systems, the implementation of 10.1 million hectares of crop-livestock-forest integration (ILPF), and the expansion of other technologies such as bio-inputs and animal waste management (Brasil, 2022).

Within the 2023/2024 "Plano Safra" (Brasil, 2023a), the main instrument for operationalizing these ambitions is the RenovAgro credit line (the successor to the ABC Program). It offers differentiated interest rates (7 to 8.5% p.a. compared to standard rates of 10 to 14% p.a.), financing limits of up to R$ 5 million per beneficiary, grace periods of up to 8 years, and additional discounts for producers with a validated Rural Environmental Registry (CAR) who adopt sustainable practices (CMN - Conselho Monetário Nacional, 2023). The fundable items cover a broad spectrum of technologies, ranging from the recovery of degraded pastures and ILPF systems to waste management and renewable energy generation.

Significant changes in the 2023/2024 Harvest Plan (Brasil, 2023a) included:

- Rebranding from the "ABC Program" to "RenovAgro";
- Differentiated annual interest rates of 7 and 8.5%;
- Increased financing limits of up to R$ 5 million per beneficiary;

- Discounts of 0.5 percentage points on the interest rate for producers with a categorized CAR who apply sustainable practices;
- Inclusion of soil conditioners and remineralizers in the Moderagro credit line.

2.2 Parameters and environmental performance indicators

The 2024–2027 PPA adopted the ratio between Total Factor Productivity (TFP) and GHG emissions in agriculture as the primary indicator of sectoral sustainability. The baseline (2012) is 1.0, with a target of reaching 1.35 by 2027 (Brasil, 2024a). This proxy indicator seeks to capture efficiency gains that reduce land-use pressure while minimizing emissions intensity. However, the TFP used in this article is a proxy for technical efficiency and does not incorporate adjustments for greenhouse gas emissions. Therefore, it should not be interpreted as a direct measure of environmental efficiency or sustainability.

National studies support the usefulness of this metric. Bragagnolo and Tateishi (2022) developed an environmentally sensitive TFP measure, while Ferreira and Vieira Filho (2024) identified that the TFP/total emissions ratio grew by 7.4% per year between 2010 and 2018, signaling an improvement in the environmental efficiency of agriculture. However, the use of simplifications such as the ratio of TFP to the volume of emissions is misguided. The indices should be calculated by considering bad outputs, such as emissions, within their equations, as suggested by Bragagnolo and Tateishi (2022).

To support spatial targeting of green credit policies, this article develops a Territorial Priority Index (TPI) combining three variables: ABC credit disbursement, degraded pasture area, and Total Factor Productivity (TFP). Each variable was normalized using the min–max method to enable comparability on a [0,1] scale. The ABC credit variable reflects cumulative disbursements (in billion BRL) under the ABC and ABC + programs from 2019 to 2023, sourced from SICOR. The Degraded Pasture variable corresponds to million hectares classified as degraded (defined by stocking rate <0.7 LU/ha) based on Embrapa's 2023 national mapping. The TFP variable is a dimensionless index (base year = 1.0) representing state-level productive efficiency.

The normalization followed the formula:

$$X_{norm} = 1 - \frac{X_i}{Xmax}$$

States with ABC credit values equal to 0.0 were verified in SICOR. If confirmed as true zero disbursements, they were retained in the model; if data were missing or incomplete, the state was excluded from index calculation. This standardization ensured balance among components and avoided dominance by any single scale.

The effectiveness of the proposed indicators is critically dependent on the existence of a robust MRV system capable of tracking and verifying the environmental outcomes of funded practices — a structure that remains incipient in Brazil. Table 1 presents the targets defined by the ABC + Plan (MAPA Ordinance No. 472/2022) and their respective mitigation potential (Brasil, 2022). While these targets reflect Brazil's ambition to promote low-emission agriculture, official rural credit programs still fund only a fraction of the investments required to meet them. This gap between credit supply and the financial scale needed for climate goals poses a significant policy challenge and underscores the urgency of aligning public credit with complementary financing mechanisms.

TABLE 1 Targets of the ABC + Plan according to MAPA Ordinance No. 472/2022 (Brasil, 2022).

ABC + technology	Target (million ha/ m^3/animals)	Mitigation target (million Mg CO_2eq)
Recovery of degraded pastures	30.0	113.7
No-till grain farming system	12.5	12.1
Crop–livestock–forest integration	10.1	34.1
Agroforestry systems	0.1	37.9
Planted forests	4.0	510.0
Bio-inputs	13.0	23.4
Irrigated systems	3.0	50.0
Animal waste management	208.4 m^3	277.8
Total	72.68 million ha + 208.4 million m^3	1,042.41 million Mg CO_2eq

Source: Adapted from Brasil (2022). Mg CO_2eq, megagrams (metric tons) of carbon dioxide equivalent.

2.3 Implementation and resource allocation gaps

Despite a well-designed policy framework, implementation faces significant challenges. Studies point to strong disparities in the allocation of ABC/RenovAgro credit resources:

- Regional and technological concentration: 65% of the resources are concentrated in the Central-West and Southeast regions, and 98% are allocated to just four technologies (Pasture Recovery, No-Till Farming, Planted Forests, and ILPF), neglecting others such as Bio-inputs and Waste Treatment (Gianetti and Ferreira Filho, 2021).
- Economic vs. environmental criteria: Credit allocation correlates more strongly with economic variables (municipal GDP and cattle herd) than with environmental indicators (area of degraded pastures), diverting resources away from areas with higher mitigation potential (Gianetti and Ferreira Filho, 2021; He, 2022).
- Bureaucratic and knowledge barriers: The complexity of administrative processes, the requirement for a validated CAR (only 6% of analyzed registrations were validated), and limited knowledge about ABC technologies among producers, technicians, and financial agents are critical obstacles (He, 2022; Gurgel, 2023).

3 Methods

This study was based on the analysis of official documents and secondary data to examine the interface between rural credit and sustainability in Brazil. The investigation began with a detailed examination of the 2023/2024 "*Plano Safra*" (Brasil, 2023a) and the 2024–2027 Pluriannual Plan (Brasil, 2024a), identifying the incentive mechanisms for sustainability and assessing their alignment with sectoral environmental targets.

To operationalize the territorial targeting of sustainable rural credit, this study developed a Territorial Priority Index (TPI) as a composite indicator. The analytical framework followed a four-step protocol based on the OECD guidelines for composite indicator construction (Munda and Nardo (2005)).

First, three core dimensions were selected: (i) Agricultural Efficiency, proxied by Total Factor Productivity (TFP); (ii) Environmental Liabilities, represented by the area of degraded pastureland (million ha) using the 0.7 AU/ha threshold (Embrapa, 2023); and (iii) Financial Gap, measured by the historical accumulated ABC credit disbursements (2019–2023).

Second, to address scale dominance and ensure comparability, all variables underwent min-max normalization, re-scaling values to a [0, 1] range. For TFP and Degraded Pasture, a direct normalization was applied, whereas for the credit history, an inverse normalization was utilized to prioritize regions with lower financial penetration.

Third, a linear additive aggregation was implemented, assuming equal weighting ($w = 1/3$) for each component to maintain policy neutrality. This structure allows for controlled compensability, where high environmental restoration potential can increase a state's priority despite its technical efficiency levels. Finally, the internal consistency of the TPI was verified through computational cross-checking of correlation and Mean Absolute Error (MAE) to ensure the robustness of the resulting priority ranking.

Model verification was conducted through an internal computational consistency check. The calculated index values were compared against the analytical formulation and the component data reported in Table 2, resulting in a near-perfect correlation (0.99986) and a very low mean absolute error (0.00085). This procedure confirms the algorithmic coherence of the index construction and the correct implementation of the formula, rather than constituting an external or empirical validation.

Spatial analysis was subsequently performed using a geographic information system implemented with Python libraries, allowing the visualization of territorial patterns derived from the index. This exploratory spatial representation supports the qualitative interpretation of convergences and divergences between observed credit allocation and the priorities suggested by the technical indicators, providing an analytical basis for policy discussion rather than predictive inference.

TABLE 2 Territorial Priority Index for sustainable credit allocation, based on historical ABC credit, degraded pasture, and total factor productivity (TFP).

State	ABC credit (BRL billions)	Degraded pasture (million ha)	TFP	Final Index
Pará	127.5	8.0	1.0268	0.759
Mato Grosso do Sul	393.8	11.9	1.0169	0.736
Bahia	337.7	10.7	0.9956	0.726
Goiás	341.2	10.0	1.0102	0.716
Rondônia	68.9	4.8	1.0035	0.710
Minas Gerais	754.2	16.8	0.9977	0.695
Rio de Janeiro	5.3	1.2	1.0879	0.689
Pernambuco	4.4	2.0	1.0007	0.677
Ceará	5.0	1.8	1.0051	0.676
Tocantins	204.1	5.4	1.0043	0.674
Amazonas	0.0	0.7	1.0565	0.672
Rio Grande do Norte	0.0	1.4	1.0037	0.669
Paraíba	3.3	1.4	0.9911	0.664
Espírito Santo	20.8	1.6	0.9788	0.658
Alagoas	0.0	0.7	1.0021	0.654
Piauí	57.9	1.5	1.0176	0.653
Sergipe	0.0	0.7	0.9961	0.652
Maranhão	156.5	3.2	1.0087	0.648
Distrito Federal	0.0	0.1	1.0082	0.644
Santa Catarina	42.2	0.8	0.9985	0.640
Acre	18.6	0.3	1.0009	0.640
Mato Grosso	906.4	15.9	1.0456	0.637
Paraná	118.7	1.6	1.0041	0.629
Roraima	38.0	0.3	0.9734	0.624
São Paulo	338.3	3.7	1.0182	0.595
Rio Grande do Sul	423.1	3.4	0.9961	0.550

Source: Research data. The index is calculated from the normalized and equally weighted combination of the three variables. A higher index indicates greater priority for sustainable credit.

4 Results

The definition of priority zones for the allocation of sustainable rural credit was based on the integration of three territorial dimensions drawn from recent literature: (i) the historical intensity of access to ABC Program credit by federative unit (Gianetti and Ferreira Filho, 2021); (ii) the extent of state-level pasture area classified as degraded, based on the technical threshold of a stocking rate below 0.7 animal units per hectare (AU/ha), as proposed by Bolfe et al. (2024); and (iii) the Total Factor Productivity (TFP) of each state. All three variables exhibit empirical robustness and policy relevance for informing emissions mitigation efforts and the restoration of productive agricultural land.

The ABC credit variable reflects the cumulative volume of disbursements per state from 2019 to 2023, measured in billions of Brazilian reais. The values were extracted from official annual rural credit reports available through SICOR/MAPA (Brasil, 2024c). No deflation was applied, since the objective was to capture historical magnitude rather than real price evolution. In states such as Rio de Janeiro, Amazonas, and Roraima, the recorded value is "0.0," which indicates a lack of formal ABC credit operations during the period, rather than missing data.

The identification of degraded pasture areas followed the technical threshold proposed by Bolfe et al. (2024), which defines pastures with

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a stocking rate below 0.7 AU/ha as degraded. This proxy is operationally robust, as it allows spatial targeting based on georeferenced livestock and land-use data. While a uniform threshold facilitates national comparison, its sensitivity to regional contexts remains a limitation. Future research may benefit from stochastic models or bioma-specific cutoffs to refine this proxy. For the current analysis, however, the 0.7 AU/ha threshold was applied consistently across all states. It is important to note that all values in the dataset are actual measurements — no imputation or substitution of missing values was performed.

The index was constructed using a weighted spatial overlay approach, where each federative unit received a composite score based on its relative position in each dimension. The principle of dimensional equity was applied, assigning equal weights ($\alpha = \beta = \gamma = 1/3$) to all three components in the absence of a normative rationale for prioritization. This approach reflects the principle of dimensional equity in the absence of a normative rationale to prioritize one variable over others. The choice of a linear additive model is supported by Munda and Nardo (2005), who argue that such models are widely used due to their simplicity and interpretability, especially when variables are measured on comparable scales and the goal is to allow full compensability between indicators. As with the other components, TFP was normalized using the min–max method. Importantly, the TFP values are not adjusted for emissions and are used solely as a proxy for technical efficiency.

The general equation adopted for the composite index was formalized as follows:

$$TPI_i = \alpha \cdot \left(1 - \frac{C_i}{C_{\max}}\right) + \beta \cdot \frac{D_i}{D_{\max}} + \gamma \cdot \frac{TPF_i}{TPF_{\max}}$$

where

- TPI = is the Territorial Priority Index for state
- $\alpha = \beta = \gamma = 1/3$
- Ci = Volume of ABC credit allocated in state i (BRL billions)
- Cmax = Maximum observed ABC credit value (BRL 906.4 billion)
- Di = rea of degraded pastures in state i (million hectares)
- Dmax = Maximum observed area of degraded pastures (16.8 million hectares)
- TPFi = Total Factor Productivity of state i

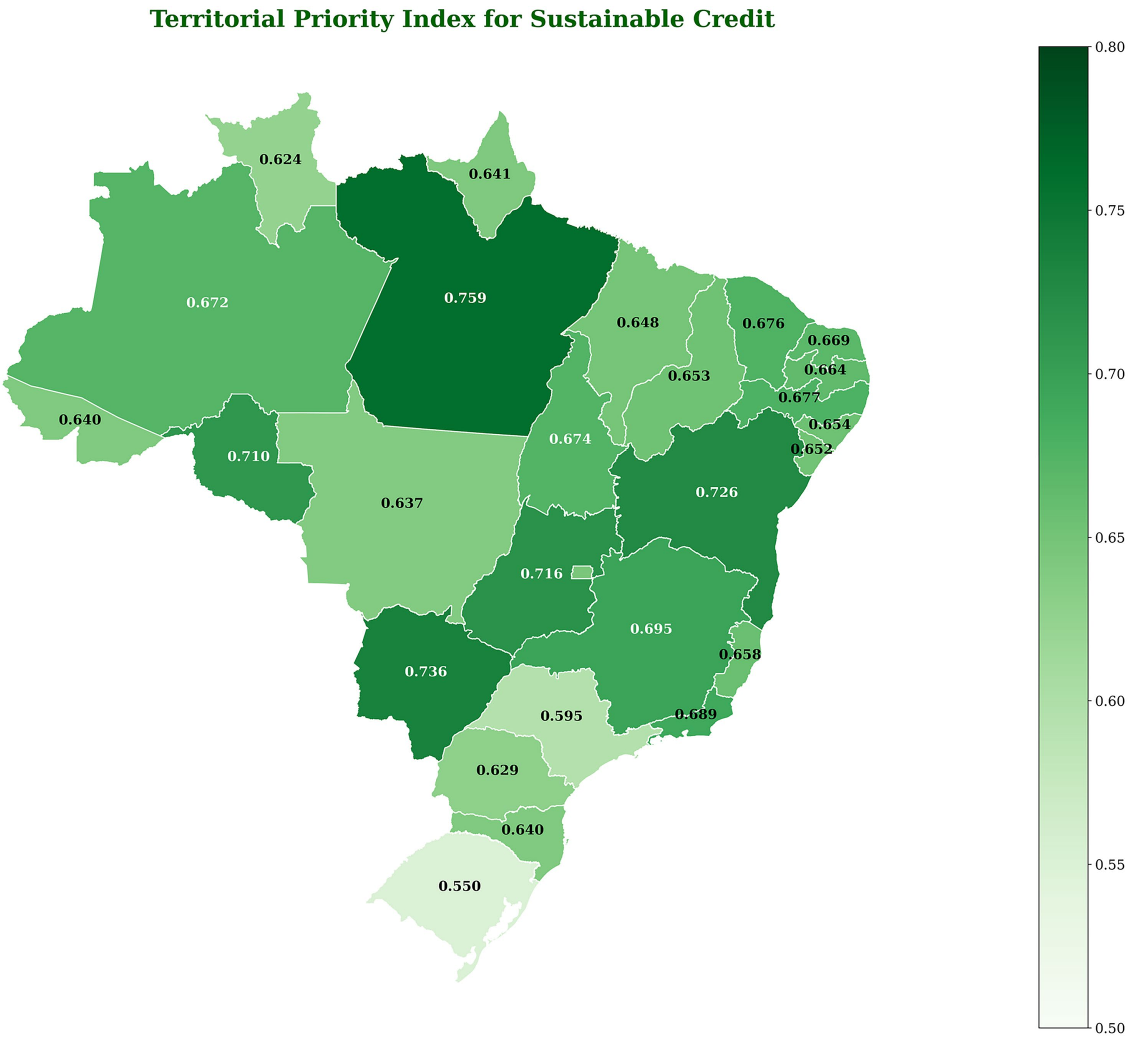

FIGURE 1
Territorial Priority Index (TPI) for sustainable rural credit allocation in Brazil. Source: Gianetti (2021) e Bolfe et al. (2024).

The result (Figure 1) identifies regions with the highest urgency for the integration of credit policies and sustainable practices, highlighting states such as Pará, Mato Grosso do Sul, Bahia, Goiás, and Rondônia as priorities.

To assess the robustness of the Territorial Priority Index (TPI) to alternative normative assumptions, a sensitivity analysis was conducted by varying the weights assigned to its three components: historical access to ABC credit, extent of degraded pastures, and Total Factor Productivity (TFP). Eight alternative weighting scenarios were defined around the baseline specification with equal weights, systematically increasing the relative importance of each dimension while preserving the unit-sum constraint.

Spearman rank correlation coefficients (ρ) measure the stability of state rankings relative to the baseline. Values close to 1.0 indicate that the ordering of priority states remains largely unchanged. The mean rank change reflects the average absolute shift in ranking position across all 27 federative units.

The results indicate that the overall structure of territorial prioritization is robust under most plausible weighting schemes. Spearman rank correlations between the baseline scenario and alternative specifications remained high in the majority of cases, exceeding 0.75 in six out of eight scenarios and reaching values above 0.95 when weights remained relatively balanced. Scenarios with extreme emphasis on a single dimension—particularly historical credit allocation—produced larger ranking shifts, as reflected in lower correlation coefficients and higher average position changes.

Importantly, the group of states identified as high-priority under the baseline specification—such as Pará, Mato Grosso do Sul, Bahia, Goiás, and Rondônia—remained among the top-ranked territories across most scenarios, indicating that the index is not driven by a single variable but by the joint contribution of production efficiency, environmental recovery potential, and credit allocation asymmetries.

Larger ranking variations were observed for states with intermediate profiles, such as Minas Gerais and Mato Grosso, suggesting that their relative priority is more sensitive to normative choices regarding policy emphasis. These results confirm that the proposed index behaves as expected for a compensatory composite indicator: it is stable for clearly prioritized territories while remaining responsive to alternative policy orientations. Full sensitivity tables and scripts are provided as supplementary material to ensure transparency and reproducibility. The sensitivity analysis confirms that the identification of high-priority territories is robust to alternative weighting schemes, reinforcing the policy relevance of the proposed index (Table 3).

The operationalization was carried out using a Geographic Information System (GIS) in Python, utilizing public libraries such as GeoPandas and Matplotlib. The result was visualized through a heat map with a clipping of the Brazilian territory, highlighting the regions with the highest urgency for the integration of credit policies and sustainable practices.

TABLE 3 Sensitivity analysis of the Territorial Priority Index (TPI) to alternative weighting scenarios.

Scenario	Weight configuration (α, β, γ)	Spearman ρ vs. baseline	Mean rank change
A	(0.50, 0.25, 0.25)	0.446	6.37
B	(0.25, 0.50, 0.25)	0.788	3.33
C	(0.25, 0.25, 0.50)	0.966	1.19
D	(0.40, 0.40, 0.20)	0.997	0.30
E	(0.20, 0.40, 0.40)	0.789	3.41
F	(0.45, 0.30, 0.25)	0.761	4.07
G	(0.30, 0.45, 0.25)	0.869	2.44
H	(0.30, 0.25, 0.45)	0.911	2.00

The baseline scenario uses equal weights ($\alpha = \beta = \gamma = 0.33$). Spearman's rank correlation coefficient (ρ) measures the stability of state rankings compared to the baseline. Mean rank change indicates the average absolute shift in ranking position across all states. Values closer to 1.0 (ρ) and 0.0 (mean change) indicate higher robustness.

5 Discussion

The methodological choice of prioritizing states with higher TFP, larger areas of degraded pasture, and a lower historical volume of sustainable credit is justified by the principle of allocative efficiency combined with the objective of reducing regional asymmetries. High TPF suggests a greater capacity to transform inputs into products with less waste, reflecting a higher social and environmental return per unit of investment. The presence of large degraded areas increases the potential for environmental transformation through productive recovery, while the volume of credit already contracted indicates the need for public direction to implement and monitor sustainable practices in more stagnant states. By uniting these dimensions into a composite index, we recognize that investing where there is already traction and capacity, while simultaneously seeking to reduce state inequalities, can generate more immediate and robust effects for ecological transition goals.

Territorial prioritization should not be interpreted as a justification for the exclusive concentration of resources in historically favored regions. On the contrary, it reinforces the logic that sustainable investments should be expanded—not redistributed—from new funding sources. The proposed strategy aims to identify territories with high efficiency potential (high TFP) and significant area suitable for restoration (degraded pasture), directing additional resources to unlock this latent capacity. Thus, instead of displacing resources from areas with high performance and already structured demand, the proposal is to expand the base of beneficiaries of sustainable credit policies, ensuring equity and efficacy in the transition to a regenerative agriculture.

Recent advances in official rural credit policy in Brazil have introduced conditional incentives for the adoption of sustainable agricultural practices. Notable is the provision of interest rate discounts for producers who are in environmental compliance (via the Rural Environmental Registry - CAR) and who adopt low-emission practices (CMN - Conselho Monetário Nacional, 2023). However, the requirement for the CAR to be "analyzed" excludes a large proportion of producers who, although technically in compliance, are still awaiting formal validation by the competent environmental agencies. This requirement creates a structural bottleneck in accessing financial incentives, penalizing farmers who already comply with environmental norms.

Furthermore, the incentive related to the adoption of "sustainable practices" lacks clear operational regulation, generating legal uncertainty and low uptake. Although these measures represent advances in environmental control, they end up restricting the use of financial instruments precisely for the regularization and recovery of degraded areas. Finally, the verification of the effective adoption of sustainable practices—such as no-till farming, crop rotation, and permanent soil cover—still faces technical and operational obstacles, with low integration into automated credit concession systems, which compromises the scalability and effectiveness of finance instruments linked to sustainability.

The analysis of the territorial allocation of sustainable rural credit in Brazil reveals a growing convergence with international initiatives aimed at the restoration of productive areas and land-based climate governance. A notable example is the RAIZ Initiative – Resilient Agriculture Investment for Net-Zero Land Degradation, launched jointly with the FAO as part of the organization's climate strategy towards COP30 (FAO – Food and Agriculture Organization of the United Nations, 2025). This initiative aims to promote scalable investments in degraded areas that offer high potential for emissions mitigation, adaptation to climate change, and regeneration of agricultural ecosystem productivity.

A methodological consideration regarding the degradation proxy used in the TPI concerns the choice of the 0.7 AU/ha threshold. This study adopts the definition established by Bolfe et al. (2024) in a prominent international study on Brazilian pasture degradation. The threshold was selected for its scientific robustness, national applicability, and alignment with geospatial databases used in public policy design. Although alternative thresholds—such as 0.5 AU/ha for severe degradation or 1.0 AU/ha for moderate degradation—could yield different absolute areas, the relative ranking of priority states is expected to remain stable under reasonable variations, as the index relies on ordinal comparisons rather than absolute values. Moreover, the framework is designed to be modular and can be updated in the future to incorporate more sophisticated degradation metrics, including soil quality indicators, biomass productivity, and remote sensing time series. For the current policy-oriented application, the Bolfe et al. (2024) threshold offers a transparent and replicable foundation for territorial prioritization.

Moreover, both models share the recognition of the importance of robust MRV systems as a precondition for investment attractiveness and access to instruments such as payments for climate results and verifiable environmental certifications. In this sense, the convergence between the proposed Territorial Priority Index and the international architecture of RAIZ can generate operational and methodological synergies, promoting a sustainable investment ecosystem focused on rural areas of high environmental risk and low access to structured finance.

The integration between the current sustainable credit prioritization proposal presented in this study and the RAIZ eligibility criteria would allow for the smart redirection of public and private resources to regions where the environmental and socio-economic benefits of recovery are most significant. This articulation would also reinforce Brazil's role as a leading pilot country for land-based climate solutions, anchored in agricultural policies focused on productive regeneration, territorial justice, and ecological resilience.

The methodological proposal for the territorial prioritization of sustainable rural credit is strongly aligned with the guidelines of the national policy for productive restoration, especially with the Brazilian Green Way program, launched by the Federal Government in 2025. The program aims to restore up to 40 million hectares of degraded or low-productivity areas, with financing directed towards sustainable agricultural practices, integrated systems, the use of bio-inputs, and rigorous socio-environmental eligibility criteria (Ministério da Agricultura e Pecuária – MAPA, 2024a,b).

The Brazilian Green Way adopts a structured restoration approach, supported by three central pillars (Ministério da Agricultura e Pecuária – MAPA, 2024a,b):

- Territorial diagnosis based on geospatial evidence of degradation and productive aptitude;
- Targeted financial instruments by production system and region;
- Robust MRV mechanisms supported by certifications and annual emissions inventories.

The program's spatial logic could utilize the Territorial Priority Index proposed in this article, which need not be tied solely to the historical investments of the ABC program but rather to indicators of pasture degradation as proxies for eligibility. This application would strengthen a unified, data-driven public policy architecture, potentially enhancing synergy between resources from the Harvest Plan (Brasil, 2023a), initiatives like RAIZ (FAO – Food and Agriculture Organization of the United Nations, 2025), and market instruments such as the Eco Invest auctions.

Furthermore, the allocation of the first USD 5.5 billion of the Brazilian Green Way program by biome—with a focus on the Cerrado (57%) and the Atlantic Forest (13%) — reinforces the importance of territorial prioritization guided by technical and environmental criteria, such as those proposed in this study. The use of composite indicators, like the index presented, can serve as an auxiliary tool in defining priority investment zones, contributing to the restoration of between 1.4 and 3 million hectares in the program's initial phase.

To translate the TPI into actionable policy, three operational layers are required. First, eligible practices must be clearly defined, including restoration of degraded pastures, implementation of integrated crop-livestock-forest systems, and adoption of no-till farming, all of which are aligned with the ABC + Plan. Second, a minimum MRV framework should be established, combining remote sensing data (e.g., pasture quality indicators) with on-the-ground verification through the Rural Environmental Registry (CAR) and third-party certifications. Third, safeguards must be designed to prevent the exclusion of producers in states with lower institutional capacity. This could include targeted technical assistance, simplified verification protocols for smallholders, and transitional grace periods before full compliance is required.

6 Conclusion

This study demonstrates that Brazil has a policy framework to align rural credit with sustainability, as evidenced by the ABC + Plan, RenovAgro, and the climate commitments of the 2024–2027 PPA. However, its effectiveness remains limited by implementation gaps, the absence of structured monitoring, and weak integration between financing and environmental outcomes.

In this context, we developed a TPI that equitably combines low historical usage of ABC credit, the extent of degraded pastures, and production efficiency measured by TFP. The results identify key states for targeted policies with high potential for positive environmental impact, providing technical inputs to strengthen synergies with programs such as RAIZ and the

Brazilian Green Way initiative. By articulating financial governance with territorial intelligence, Brazil has the opportunity to transform rural credit into a strategic lever for ecological transition in agriculture.

Furthermore, the study has raised a set of interconnected proposals: strengthen territorial-based MRV systems; direct resources based on clear geospatial criteria; formalize incentives with the official recognition of sustainable certifications; and expand technical assistance, especially for low-emission technologies that are still not widely adopted. Concurrently, refining the Total Factor Productivity (TFP) indicator adjusted for emissions is crucial for the continuous assessment of environmental performance.

Author contributions

LR: Methodology, Investigation, Conceptualization, Project administration, Formal analysis, Writing – original draft. EM: Investigation, Supervision, Writing – review & editing, Writing – original draft, Validation, Data curation. MG: Writing – review & editing, Validation, Methodology. BB: Supervision, Writing – review & editing, Data curation, Project administration. JN: Conceptualization, Methodology, Project administration, Writing – review & editing, Supervision. RC: Supervision, Writing – review & editing, Project administration.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. Generative AI was used exclusively to assist in the development, debugging, and optimization of Python code employed for statistical analyses and data visualization. No generative AI tools were used to produce, draft, or edit the scientific arguments, interpretations, discussion, or conclusions of the manuscript. The authors take full responsibility for all analyses, results, and the scientific content of this work.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1757578/full#supplementary-material

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