frontiers in Sustainable Food Systems

TYPE Policy and Practice Reviews
PUBLISHED 02 June 2026
DOI 10.3389/fsufs.2026.1774282

OPEN ACCESS

EDITED BY
Philip Thornton,
Agriculture and Food Security (CCAFS), Kenya

REVIEWED BY
Raffaella Pergamo,
Council for Agricultural Research and Agricultural Economy Analysis | CREA, Italy
Adriane Terezinha Schneider,
Universidade Federal de Santa Maria, Brazil
Marcos Aurélio Santos Da Silva,
Embrapa Tabuleiros Costeiros, Brazil

*CORRESPONDENCE
Luis Eduardo Pacifici Rangel
✉ luiseduardorangel76@gmail.com

RECEIVED 23 December 2025
REVISED 04 May 2026
ACCEPTED 08 May 2026
PUBLISHED 02 June 2026

CITATION
Rangel LEP, Domiciano GP, Arruda GMT, Silva CSdS, Guimarães MF, Venâncio CR, Brasil BdSAF, Nogueira JM and Carmona R (2026) The national sustainable taxonomy proposals and their implications for agribusiness. *Front. Sustain. Food Syst.* 10:1774282. doi: 10.3389/fsufs.2026.1774282

The national sustainable taxonomy proposals and their implications for agribusiness

Luis Eduardo Pacifici Rangel[1,2,3]*, Gisele Pereira Domiciano[2], Giovana Maria Tadaieski Arruda[2], Camila Stefani de Souza Silva[4], Marcelo Fernandes Guimarães[1], Carlos Ramos Venâncio[1], Bruno dos Santos Alves Figueiredo Brasil[5], Jorge Madeira Nogueira[6] and Ricardo Carmona[3]

[1]Ministry of Agriculture and Livestock, Brasília, Brazil, [2]Instituto de Desenvolvimento Sustentável - IDS, Brasília, Brazil, [3]Faculty of Agronomy and Veterinary Medicine, Universidade de Brasilia, Brasília, Brazil, [4]Ministério da Fazenda, Brasília, Brazil, [5]Embrapa, Brasília, Brazil, [6]Depart of Economics, Universidade de Brasilia, Brasília, Brazil

The consolidation of sustainable finance taxonomies within financial systems marks a critical juncture for global agriculture. This article examines the Brazilian Sustainable Taxonomy (BST) and argues that its effectiveness depends on a design that balances environmental ambition with sectoral realities, avoiding unintended penalties for compliant producers. The analysis shows that broad exclusion criteria—such as prohibiting activities based on legally permitted deforestation or generic toxicological classifications—can be counterproductive. Such approaches risk creating regulatory distortions and undermining practices like integrated pest management. A shift toward a performance-based, incentive-driven model is therefore warranted. Empirical evidence supports the use of percentile-based thresholds (e.g., P85, P90) applied to the Environmental Impact Quotient (EIQ) to identify and restrict high-risk inputs more precisely. In parallel, recognizing Legal Reserve (LR) surpluses as assets eligible for financial compensation would better align conservation incentives with producer behavior. This dual-frontier approach, combined with robust digital Monitoring, Reporting, and Verification (MRV) systems, enables a continuous rather than binary pathway to sustainability. A scientifically grounded and interoperable taxonomy can thus evolve from a classification framework into an operational green finance architecture, positioning Brazilian agriculture to reconcile productivity with climate commitments and biodiversity conservation.

KEYWORDS
agricultural sustainability, biodiversity, public policies, sustainable finance, sustainable taxonomy

1 Introduction

The transition to sustainable agricultural systems has become a central pillar of climate policy and agricultural development. In Brazil, established technologies—such as no-till farming (Sá et al., 2025), biological nitrogen fixation (BNF) (Telles et al., 2023), and crop-livestock-forest integration (CLFI) (Reis et al., 2025)—demonstrate the feasibility of reconciling high productivity with emission reductions. This positions the country strategically within the global low-carbon agenda, particularly within a context where agriculture functions simultaneously as both carbon source and sink.

Brazil's tropical conditions, combined with its diversity of biomes and the robust legal framework of the Forest Code, enable agricultural expansion to occur in a regulated manner, with mitigation potential rooted in both conservation and the improvement of productive systems (Brock et al., 2021). However, realizing these opportunities depends on regulatory instruments capable of differentiating sustainable practices, assessing environmental risks, and steering financial flows consistent with on-the-ground realities. In this study, sustainability is understood as the integration of economic viability, social equity, and environmental conservation, with emphasis on instruments that provide measurable ecological and financial performance indicators.

The Brazilian Sustainable Taxonomy (BST) (Brasil, Ministério da Fazenda, 2025) emerges as one such instrument, proposing criteria to characterize sustainable agricultural activities. Unlike taxonomies from temperate countries, the BST must address unique challenges, such as distinguishing between legal and illegal deforestation, accommodating technological heterogeneity across regions, and recognizing transitional pathways—not just final states of sustainability. Its development, therefore, demands careful design to avoid distortions that could undermine access to rural credit, competitiveness, and legal security for producers.

Given this context, the objective of this study is to critically evaluate two central aspects of the BST: (i) the treatment of legal deforestation in the classification of agricultural activities and its effects on credit eligibility; and (ii) the classification of pesticides based on internationally recognized environmental risk metrics. The analysis aims to contribute to a taxonomy that is technically consistent, aligned with the tropical context, and capable of promoting a low-carbon agriculture without compromising regulatory predictability.

2 Background

2.1 Agricultural sustainability and Brazil's role in the climate agenda

Scientific literature highlights that sustainable agricultural systems are essential for reducing emissions, enhancing climate resilience, and maintaining long-term productivity (Eyhorn et al., 2019; Kassam, 2023; Oliveira et al., 2023; Monteiro et al., 2024). Brazil presents a unique set of conditions to advance in this direction: high agricultural productivity, the growing adoption of conservation technologies, and a robust legal framework for the protection of native vegetation. Technologies such as no-till farming (Maia et al., 2022), Biological Nitrogen Fixation (FNB) (Hungria and Nogueira, 2022), and CLFI (Nwaogu et al., 2024) have already demonstrated significant impacts on emission mitigation and soil quality improvement.

2.2 Legal framework and productive heterogeneity

The Forest Code (Law 12.651/2012) establishes rigorous parameters for maintaining protected areas and the environmental regularization of rural properties (Brasil, 2012). However, the application of these standards occurs within a highly heterogeneous territorial context: six distinct biomes with varying ecological, productive, and climatic capacities. This variability affects both the costs of environmental compliance and the feasibility of sustainable practices (Nascimento et al., 2025). Consequently, financial policies and classification instruments—such as a sustainable taxonomy—must reflect this diversity and avoid importing criteria designed for temperate realities.

Moreover, agricultural productivity in Brazil is marked by substantial regional disparities, with significant yield gaps persisting across different biomes and production systems, particularly in livestock and low-technology farming. These gaps create an opportunity cost between two alternative development pathways: investing in technological intensification on already cleared land or expanding agricultural frontiers into native vegetation areas. A sustainable taxonomy must, therefore, not only reflect territorial diversity but also actively incentivize practices that close yield gaps while preserving native ecosystems.

2.3 Sustainable taxonomies and economic transition

The rise of green taxonomies emerges as a global response to the need for directing financial flows towards activities with lower environmental impact. However, rigid binary models, such as the European Taxonomy, tend to exclude sectors in transition or those dependent on gradual improvements. The BST proposes a progressive and adaptive model capable of recognizing transitional pathways and sustainable intensification practices, aligning more effectively with tropical reality (Schütze and Stede, 2024).

2.4 Theoretical foundation: environmental, ecological, and green economics

The debate on sustainable taxonomies and financial instruments is supported by three theoretical frameworks. Environmental economics emphasizes the internalization of externalities and the valuation of natural resources; ecological economics underscores biophysical limits and the need for productive reorganization; and green economics proposes incremental adjustments within the existing economic model (Oliveira, 2017). Models such as the Environmental Kuznets Curve (Grossman and Krueger, 1995) and more recent approaches, like post-Keynesian environmental macroeconomics (Alvarenga Junior and Young, 2021), reinforce that environmental improvements depend on active policies, targeted incentives, and robust regulatory instruments.

2.5 Financial regulation and socio-environmental risks

In Brazil, the Socio-Environmental Responsibility Policy (PRSA) determines that financial institutions monitor deforestation risks within their portfolios (Nogueira et al., 2015). The BST should, therefore, complement, not duplicate, this existing framework. A critical element is the recognition of established instruments like the Environmental Reserve Quota (abbreviated as CRA in Portuguese), which internalizes the value of conservation by allowing compensation for Legal Reserve (LR) deficits. Studies indicate that the CRA can reduce compliance costs by up to 76% without compromising ecological integrity (May et al., 2016).

2.6 Rural credit, deforestation, and legal security

The relationship between rural credit and deforestation is complex: credit can finance productive expansion onto new land or consolidate sustainable systems in already cleared areas. Literature shows this relationship depends on the type of credit, on the region, and on conditions of environmental monitoring (Assunção et al., 2023). The BST must clearly differentiate between illegal deforestationand legally authorized land conversion under the Forest Code. Overlooking this distinction risks causing undue financial exclusion and undermining legal security within the agricultural sector.

2.7 Pesticides: environmental risk and impact-based metrics

The classification of pesticides is another critical point for agricultural taxonomy. Globally, pesticide use has increased significantly in recent decades (FAO, 2022), but the volume applied is an inadequate proxy for environmental risk. The literature emphasizes risk-based metrics, such as the Environmental Impact Quotient (EIQ), which account for toxicity, persistence, environmental mobility, and exposure (Kovach et al., 1992; Möhring et al., 2019). These metrics offer a more precise alternative to traditional hazard indices and allow for the differentiation of safer chemical management practices.

2.8 Interdisciplinary integration for transition policies

Designing a tropical taxonomy demands an interdisciplinary approach that connects environmental economics, soil science, financial regulation, and legal analysis. International and national studies reinforce that sustainable financial instruments must reflect not only environmental criteria but also economic viability, institutional capacity, and governance parameters (Banerjee and Duflo, 2012; Inderst and Opp, 2025). This convergence is essential to ensure that the BST promotes productive inclusion, reduces risks, strengthens regulatory credibility, and accelerates the transition towards agricultural systems with a lower climate impact.

3 Methods

3.1 Estimation of the economic potential of native vegetation surplus in rural properties by biome

The economic potential of the legal surplus of native vegetation was estimated through the integration of public geospatial and economic databases. Three primary variables were considered: (i) total area of legal surplus (ha), (ii) potential carbon value (BRL/ha), and (iii) percentage of area validation in the Rural Environmental Registry (abbreviated as CAR in Portuguese). Area and validation data were sourced from the Brazilian Forest Service (SFB) and the National Rural Environmental Registry System (Serviço Florestal Brasileiro (SFB), 2024), while land cover and use information was extracted from MapBiomas—Collection 9.0 (2024).

It is important to acknowledge the inherent limitations of the datasets used in this study. MapBiomas' classifications, while comprehensive, may present regional inaccuracies due to satellite imagery resolution and algorithmic interpretations. Additionally, the Rural Environmental Registry (CAR) is self-declaratory in nature and may not fully reflect on-the-ground conditions. Therefore, the empirical findings should be interpreted as exploratory, providing indicative evidence rather than definitive conclusions.

The potential carbon value was calculated by multiplying the average carbon stock per biome (tC/ha) according to Brasil, Ministério da Ciência, Tecnologia e Inovações (2023) and Shukla et al. (2024) by the average reference price of forest carbon credits in the Brazilian voluntary market (Lima, 2024). The calculations and spatial integrations were performed in Python (v3.11), with values expressed in Brazilian Reais (BRL) and corrected to the base year 2024 using the official inflation index.

3.2 Analysis of rural credit, legality, and territorial efficiency

Annual rural credit data (2013–2024) were obtained from the Central Bank of Brazil (BACEN/SICOR), while deforestation data were extracted from the Project for Monitoring Deforestation in the Brazilian Amazon by Satellite (PRODES) of the National Institute for Space Research. Variables were aggregated by state and normalized by total agricultural area (ha) (Banco Central do Brasil, 2024; Instituto Nacional de Pesquisas Espaciais, 2024).

The relationship between total rural credit (BRL billions) and deforested area (ha) was initially explored through bivariate scatter plots with overlays of continuous heatmaps representing emission density (tCO_2eq/ha). Analyses were conducted in Python (v3.11).

3.3 Estimation of the credit-deforestation elasticity

The relationship between rural credit and deforestation was assessed through the estimation of elasticity parameters using a log–log specification. In this framework, elasticity is defined as:

$$\varepsilon = \frac{d(\ln D)}{d(\ln C)} = \beta_1$$

Where D represents annual deforestation (ha) and C represents sustainable credit (BRL). The time series (2013–2024) were log-transformed to reduce heteroscedasticity, and the β_1 to be interpreted as the percentage change in deforestation associated with a 1% change in credit.

To ensure consistency between the theoretical definition and the empirical implementation, the elasticity was estimated using the following panel data specification:

$$\ln(D_{it}) = \beta_0 + \beta_1 \ln(C_{it}) + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where i indexes states and t indexes time. The vector X_{it} includes control variables such as agricultural GDP, commodity prices, and total agricultural area. State fixed effects (μ_i) account for time-invariant heterogeneity across regions, including structural and institutional differences, while time fixed effects (λ_t) capture common shocks affecting all units, such as macroeconomic conditions and national policy changes.

All variables were transformed into natural logarithms to reduce heteroscedasticity and allow for elasticity interpretation. The model was estimated using Ordinary Least Squares (OLS) with fixed effects.

3.4 Analysis of the environmental impact of pesticides (EIQ) and ecological factor

The relationship between the Environmental Impact Quotient (EIQ) and the ecological factor was analyzed for a dataset of 87 active ingredients compiled from official pesticide registration databases in Brazil (IBAMA, 2025; Brasil, Ministério da Ciência, Tecnologia e Inovações, 2023; Brazilian Institute of Environment and Renewable Natural Resources, 2025), the United States (United States Environmental Protection Agency (EPA), 2025), the European Union (European Commission, 2025), and Japan (Food and Agricultural Materials Inspection Center, 2025). For analytical purposes, active ingredients were classified into three regulatory categories: (i) Restricted, comprising substances subject to regulatory limitations in at least one jurisdiction; (ii) Not Restricted, including substances approved without major regulatory constraints across jurisdictions; and (iii) Escape, defined as cases in which the same active ingredient appears under different regulatory classifications across countries or formulations, without corresponding differences in measured environmental impact. This category captures inconsistencies arising from formulation changes or jurisdiction-specific criteria that allow substances with similar risk profiles to be classified differently.

The analysis was conducted using a structured data matrix (see Supplementary material), enabling the comparison of EIQ values and ecological factors across regulatory categories and jurisdictions. Statistical analyses—including normality tests, inter-group comparisons, and checks for significant differences—were conducted. The non-parametric Kruskal–Wallis test was applied due to the absence of normality and homoscedasticity in the data series ($p < 0.05$).

3.5 Evidence of "regulatory escape"

The hypothesis of regulatory escape was evaluated by comparing the mean EIQ and ecological factor values across the three regulatory groups (Restricted, Not Restricted, and Escape). Verification of statistically significant differences between the groups was performed using the non-parametric Kruskal–Wallis test ($p < 0.05$), due to the absence of normality and homoscedasticity in the data. Complementary analyses, including descriptive statistics, multiple comparison tests, and graphical inspection of the distributions are available in the Supplementary material.

4 Results

4.1 Legality versus sustainability: quantitative evidence of native vegetation surpluses

As evidenced in Table 1, Brazil holds approximately 19 million hectares of legal surplus native vegetation, with a strong concentration in the Amazon and Cerrado biomes, which together account for over 75% of this potential. In contrast, the Pampa and Pantanal biomes exhibit a lower volume of LR surplus, reinforcing significant regional differences relevant for public policy.

The estimated carbon value associated with LR surpluses should be interpreted as theoretical gross potential rather than directly realizable economic value. The calculation is based on average carbon stocks and reference prices in voluntary carbon markets, and does not account for critical constraints such as market liquidity, additionality requirements, permanence risks, transaction costs, and verification protocols. Furthermore, the effective monetization of these assets depends on the development of robust MRV systems and regulatory frameworks capable of ensuring environmental integrity and avoiding double counting. Therefore, the estimates presented here serve as an indicative measure of the potential magnitude of environmental assets, rather than a forecast of actual financial returns.

4.2 Credit, legality, and territorial efficiency: empirical findings

The data show that deforestation totaled 8.67 million hectares between 2019 and 2024, concentrated in the Amazon (4.8 million ha) and the Cerrado (3.87 million ha) biomes. Overall correlations suggest a very weak relationship between deforestation and financial variables, such as: total financing (+0.062), Agricultural Gross Production Value (+0.017), and commodity prices (+0.07 to +0.14). Rural credit shows a slightly negative correlation (−0.051), indicating that an increase in credit, in isolation, does not drive deforestation expansion. In Figure 1, the local coefficient of −0.023 reinforces that states with low financial leverage may exhibit high deforestation due to structural, non-credit-related factors.

Figure 1 reveals high-impact zones, particularly in the Amazon biome, where high credit volumes coexist with elevated deforestation rates, contrasting with regions of relative efficiency, such as the

TABLE 1 Economic potential of LR surplus by biome: area (ha), potential carbon value (BRL/ha), and percentage validated in the Rural Environmental Registry (CAR).

Biome	LR surplus (ha)	Average carbon stock (tC/ha)*	Total carbon (MtC)	CO_2e ($MtCO_2e$)	Carbon price (BRL/tCO_2)	Total value (BRL bi)
Amazon	8,524,193	148	1,262.6	4,634.8	75	347.6
Cerrado	5,715,849	69	394.4	1,447.4	75	108.6
Atlantic Forest	2,503,584	118	295.4	1,084.1	75	81.3
Caatinga	1,930,812	54	104.3	382.7	75	28.7
Pampa	170,176	61	10.4	38.3	75	2.9
Pantanal	345,275	112	38.7	141.9	75	10.6
Total Brazil	19,189,889	—	2,105.8	7,729.2	—	579.7

*Average carbon stock values (tC/ha) were calculated using a weighted mean based on the proportional contribution of each phytophysiognomy within the biome (Brasil, Ministério da Ciência, Tecnologia e Inovações, 2023).
Conversion factor: 1 tC = 3.67 tCO_2 (Brasil, Ministério da Ciência, Tecnologia e Inovações, 2023).
Reference voluntary carbon price: BRL 75 per tCO_2 (≈ USD 15 per tCO_2).

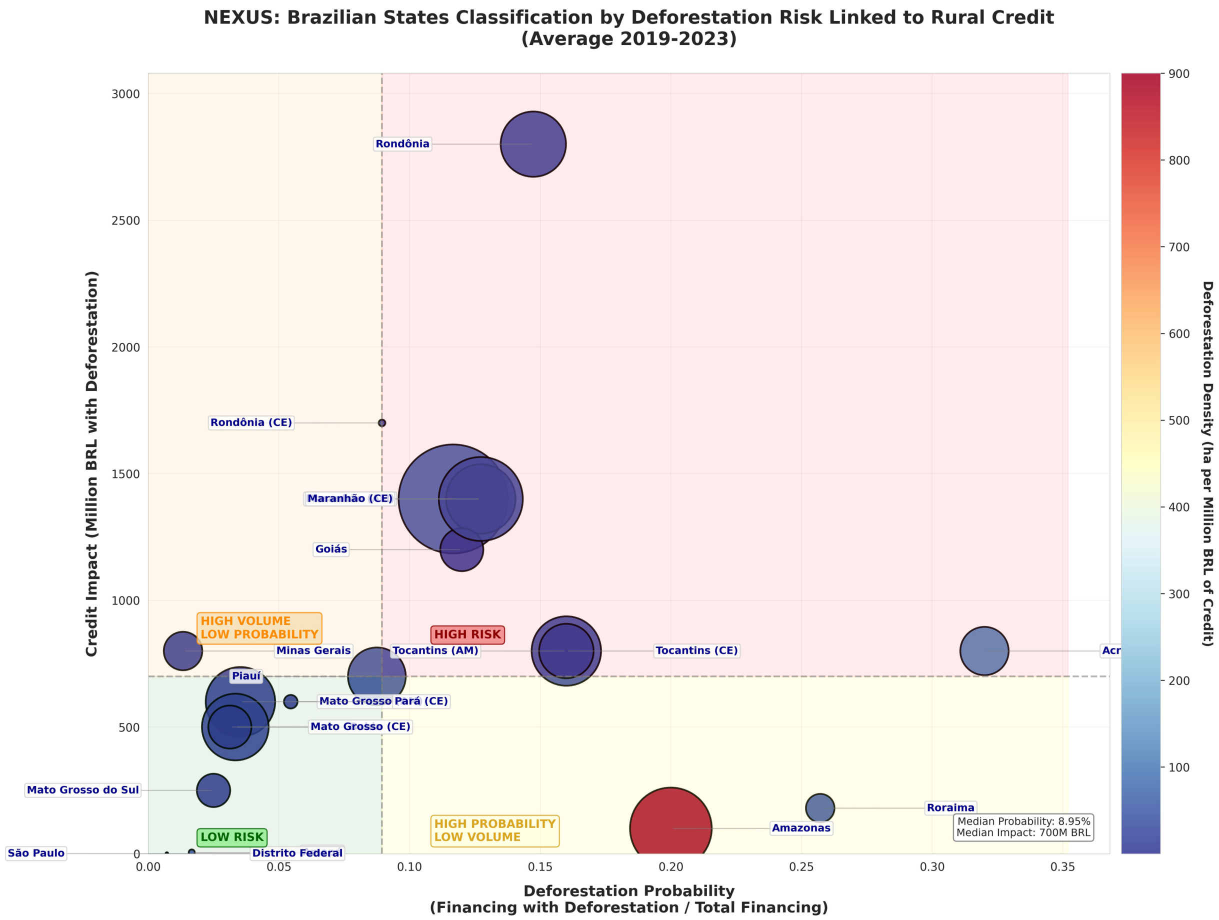

FIGURE 1
Brazilian states classified by deforestation risk associated with rural credit (average 2019–2023).

Cerrado. The estimated linear models present low explanatory power ($R^2 < 0.05$), indicating that rural credit, in isolation, explains only a small fraction of the observed variation in deforestation. Rather than undermining the analysis, this result reflects the structural complexity of land-use dynamics in Brazil. Only the biome effect was statistically significant, reinforcing that territorial and productive conditions play a more decisive role than the aggregate level of credit.

In this context, deforestation is driven by a combination of territorial, institutional, and economic factors—including land tenure conditions, enforcement capacity, infrastructure expansion, and regional production systems—while credit operates as a complementary factor, whose effects are mediated by local conditions, rather than as a primary driver. This interpretation is consistent with the observed spatial heterogeneity and highlights the limitations of aggregate financial indicators. Overall, the results reinforce the need for more refined, territorially differentiated metrics to guide sustainable finance and environmental policy.

Regarding elasticities, the results presented in Table 2 reveal significant spatial heterogeneity. Negative values in Cerrado states, such as Goiás (−0.394) and Mato Grosso do Sul (−0.168), contrast with high positive values in Amazonian states, such as Pará (+206.6) and Rondônia (+19.9).

The estimated elasticities exhibit substantial variability across states, including extreme values in specific regions, which suggests sensitivity to local conditions and potential instability in the estimates. In this context, robustness checks—including the exclusion of extreme observations and the use of alternative specifications—confirm that the overall pattern remains unchanged. At the aggregate level, the results indicate that no systematic linear relationship is observed between rural credit and deforestation (Figures 2–4).

A potential limitation of empirical specification concerns endogeneity and reverse causality between rural credit and deforestation. Credit allocation may respond to land-use dynamics, while both variables may be jointly determined by omitted factors such as enforcement intensity, land prices, and institutional capacity. Therefore, the estimated elasticities should be interpreted as conditional associations rather than causal effects, consistent with the literature on credit and deforestation dynamics (Assunção et al., 2023, 2015).

Taken together, these results suggest that deforestation dynamics are primarily driven by structural and territorial factors, rather than by the isolated effect of credit availability. This reinforces the need for spatially differentiated policy instruments and more refined indicators to guide sustainable finance strategies.

4.3 Toxicological classes: comparative evidence and risk distribution

The comparative analysis of 87 active ingredients (AIs) shows that applying broad exclusions—such as prohibiting IBAMA classes I to III—would render ineligible for classification as sustainable under the BST approximately 70% of Integrated Pest Management (IPM) portfolios, including widely recognized sustainable systems like No-Till

10.3389/fsufs.2026.1774282

TABLE 2 Territorial efficiency indicators of rural credit.

State	Biome	Average sustainable credit (BRL)	Average deforestation (ha)	Credit–deforestation elasticity
Acre	Amazon	189,413.318	58,688.8	+0.113
Bahia	Cerrado	842,655.67	116,363.4	+0.517
Goiás	Cerrado	1,798,218.64	43,073.3	−0.394
Maranhão	Amazon	1,274,879.344	100,360.3	−4.703
Mato Grosso	Amazon	2,170,517.115	92,149.4	+0.382
Mato Grosso do Sul	Cerrado	1,335,654.383	28,870.9	−0.168
Minas Gerais	Cerrado	475,846.66	38,294.8	−0.122
Pará	Amazon	1,361,336.996	170,609.3	+206.567
Piauí	Cerrado	503,527.747	97,035.4	+1.157
Rondônia	Amazon	268,113.409	47,468.2	+19.873

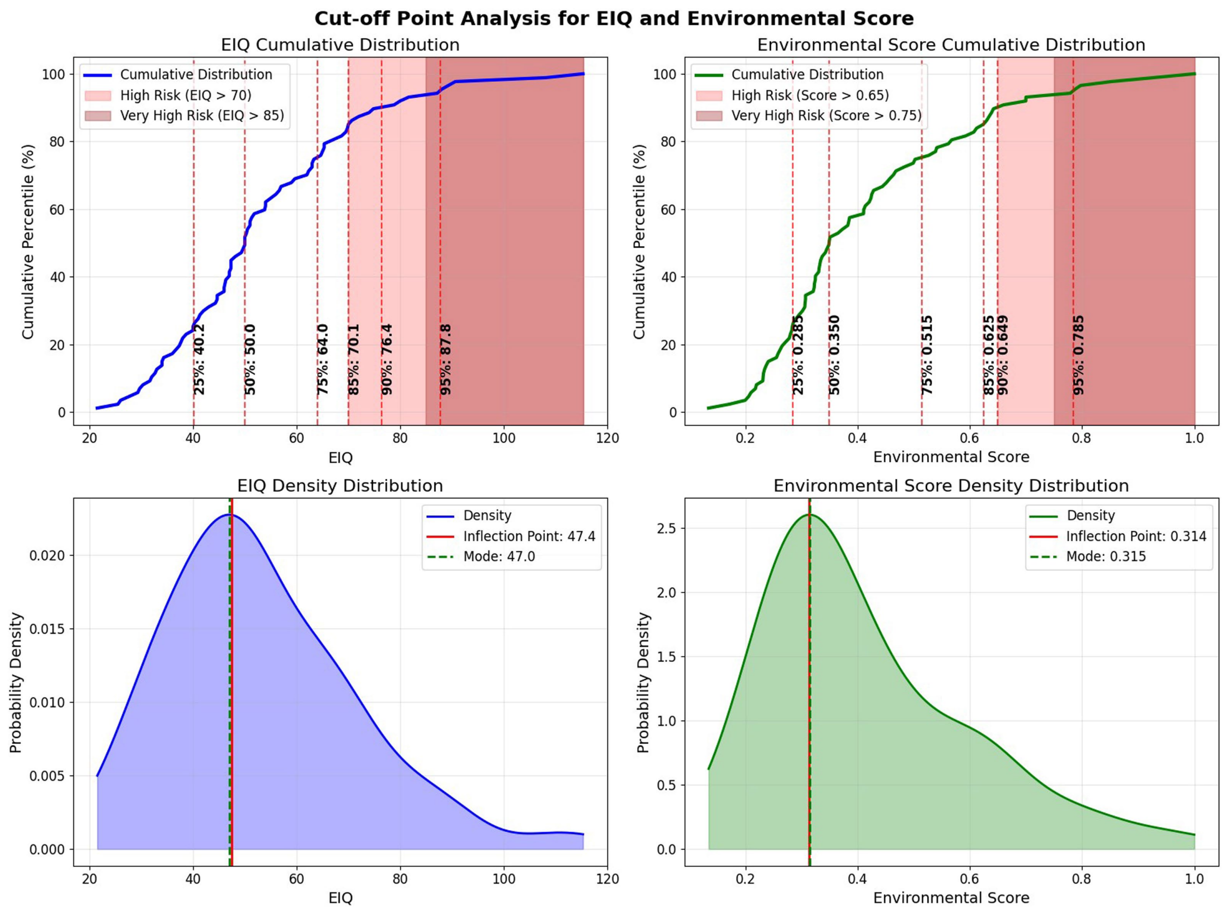

FIGURE 2
Cumulative and density distributions of environmental impact quotient (EIQ) and environmental score with risk thresholds.

Farming, which is intrinsically linked to herbicide use (Obregon et al., 2025).

The comparative results demonstrate that regulatory escape is not an exception but a structural pattern in the AI market. As the graphs show, AIs classified into different regulatory categories ("Restricted," "Not Restricted," and "Escape") exhibit a similar distribution across normalized EIQ and Ecological Factor values. This indicates that the hazard attributed by risk classification models does not correspond to the effective environmental impact of the molecules. The consistent presence of products with high EIQ values in both restricted and non-restricted groups—alongside numerous cases of "escape," where alternative formulations shift the toxicological classification without altering the actual risk, demonstrates that hazard classification is an inadequate indicator for financial eligibility criteria or exclusions in sustainable taxonomies. These findings reinforce that metrics based on measurable impact, rather than solely on

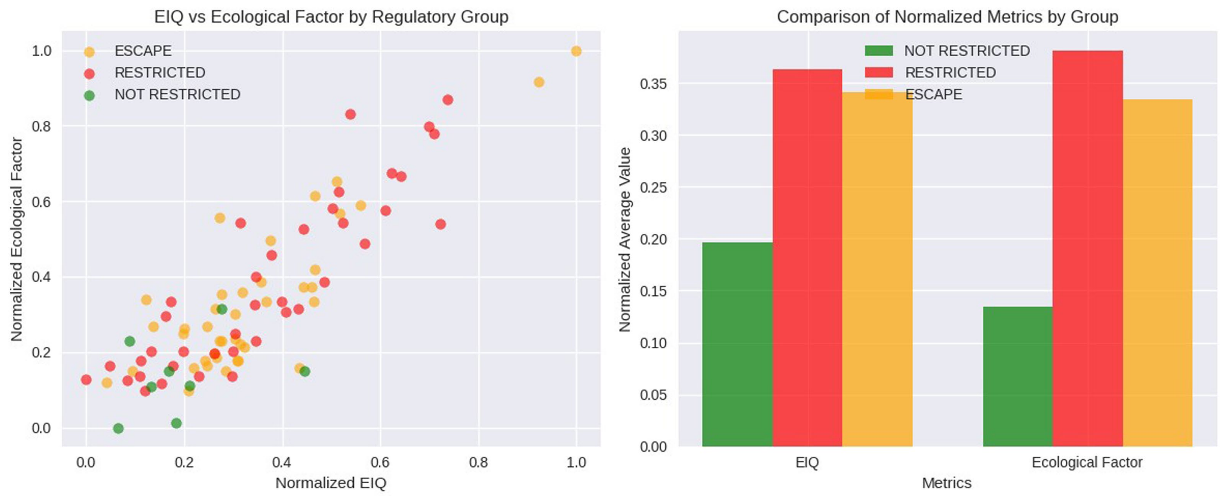

FIGURE 3
Relationship between normalized EIQ and ecological factor across regulatory groups.

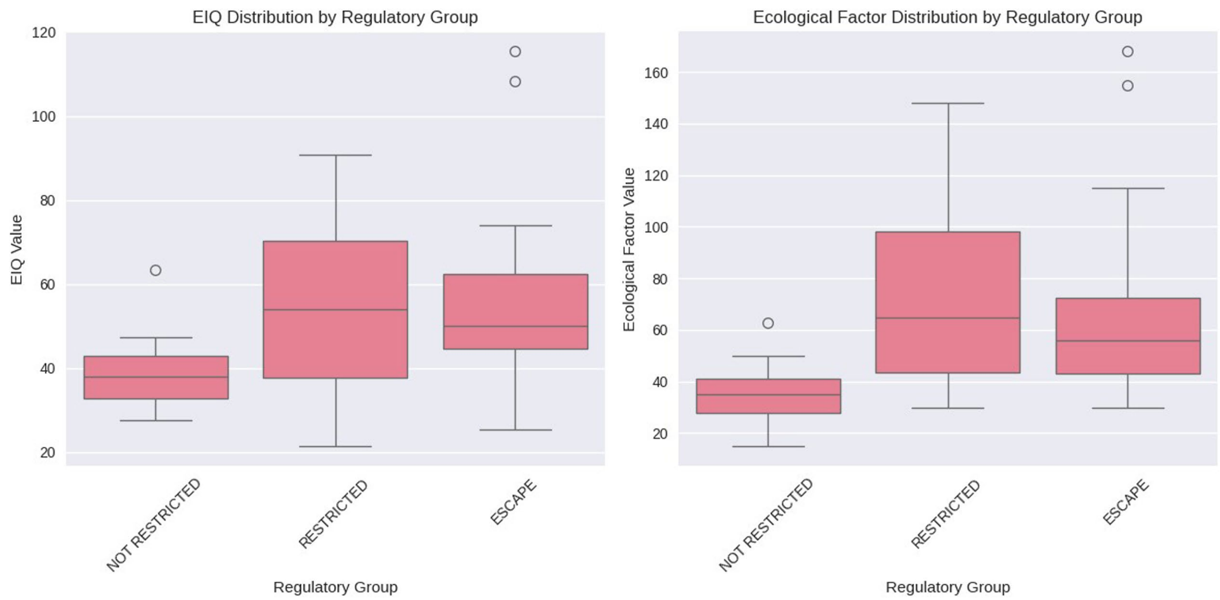

FIGURE 4
Distribution of EIQ and ecological factor by regulatory classification group.

normative categories, are essential to avoid distortions and inefficient regulatory choices.

4.4 Evidence of "regulatory escape" through formulation changes: observed data

The analysis of commercial registrations demonstrates that the same active ingredient may be classified into distinct toxicological categories (e.g., Anvisa Classes III and IV) depending on formulation-specific components, with cases such as abamectin and thiodicarb illustrating this variability. This finding highlights the sensitivity of regulatory classification to formulation characteristics rather than to intrinsic properties of the active ingredient.

The statistical comparison of the three regulatory groups shows average EIQ values of 55.5 for restricted pesticides, 53.5 for escape formulations, and 39.9 for non-restricted substances. The Kruskal–Wallis test did not detect statistically significant differences between the groups ($p > 0.05$), indicating that regulatory classification does not correspond to systematic differences in environmental impact as measured by EIQ. This result reinforces the interpretation that hazard-based regulatory categories may not adequately reflect effective environmental risk.

4.5 Sustainability percentiles: distribution structure of EIQ

The distributional analysis of EIQ and a composite Environmental Score reveals a right-skewed, long-tailed distribution, with upper percentiles isolating cases of greater environmental impact: P85 ≈ 70, P90 ≈ 76, P95 ≈ 87. These thresholds identify the 10–15% of management programs with the highest risk.

4.6 Additional territorial evidence (CAR)

The empirical analysis of the CAR database shows that approximately 9 million hectares of surplus vegetation exist as a public environmental asset, yet without any fiscal recognition. This area could be integrated into compensation mechanisms through tradable instruments such as CRA or the Green Rural Product Note (CPR-Verde).

5 Discussion

In summary, the empirical results indicate a significant stock of native vegetation surplus, strong territorial heterogeneity in the credit-deforestation relationship, the inadequacy of using toxicological classes as a financial criterion, the utility of percentile-based approaches using EIQ, and evidence of "regulatory escape" through product reformulation of pesticides. Against this backdrop, the following discussion integrates normative and instrumental arguments.

5.1 Taxonomy operationalization: measurement, verification, and incentives design

To begin, clauses that classify as unsustainable any property that has legally cleared native vegetation in full compliance with the Forest Code create a series of regulatory distortions. First, they are unfair to producers who have rigorously complied with environmental legislation. Second, they are counterproductive for conservation, as they penalize those who maintain LR and Permanent Preservation Area surpluses, thereby reducing the economic incentive to conserve beyond the legal minimum. Third, they may generate perverse effects, such as the preemptive clearing of legally authorized vegetation before rules take effect, in an attempt to avoid future penalties.

Thus, a sustainable taxonomy cannot invert the logic of the Forest Code. In other words, compliance with the law cannot be interpreted as a sign of environmental risk but should be a precondition for eligibility. Considering the observed results, integrating surpluses into the BST creates space for financial instruments like the CRA and CPR-Verde, enabling the transformation of conserved native vegetation, an undervalued asset today, into a verifiable mechanism for generating environmental and fiscal value for compliant producers.

Furthermore, when examining territorial and institutional performance, the findings suggest that governance and institutional capacity explain deforestation reduction more than the level of credit itself. Additionally, the Agricultural Gross Production Value (VPB Agro) is associated with deforestation intensity, indicating that leveraging territorial competitive advantages may be a more efficient pathway to reconcile production and conservation. Therefore, the magnitude and sign of the elasticities reinforce the need to calibrate the BST based on the marginal efficiency of credit, prioritizing not only the volume financed but also its net impact on native vegetation preservation. In this same vein, incorporating mechanisms such as Payments for Environmental Services (PSA), CRA, and CPR-Verde increases the financial resilience of conservation areas and converts legality into an economically recognized market asset in regions with mature institutional development.

Regarding inputs and management, a point of regulatory caution emerges: the toxicological classes of ANVISA (Brazilian Health Regulatory Agency) and the environmental hazard classes of IBAMA (abbreviated as PPA in Portuguese and equivalent to environment risk assessment in others contries) were designed for labeling, prescription, and risk mitigation in handling and application of pesticides, not as binary criteria for financial eligibility. The application of broad exclusions, for instance for active ingredients (AIs) classified in classes I to III, would render the majority of Integrated Pest Management (IPM) portfolios ineligible, including widely recognized sustainable systems like no-till farming (Obregon et al., 2025).

Moreover, the weak convergence between risk measurement systems (EIQ) and labeling classifications—exemplified by substances like clothianidin and abamectin, which have products classified as ANVISA Class 4 but IBAMA Class III—highlights the danger of using inadequate models as indicators for sustainable credit. This creates legal uncertainty and competitive distortions. Considering the empirical results, adopting percentile-based risk criteria (instead of prohibitions by class) preserves IPM functionality and avoids disproportionate exclusions.

This caveat becomes even more relevant considering "regulatory escape" evidence: divergent classifications for the same active ingredient tend to shift the market towards alternative formulations with the same AI, thereby circumventing sustainability objectives, increasing compliance costs, and distorting competition. This demonstrates that toxicology of formulations does not adequately reflect the active ingredient's risk, making it an inadequate proxy for taxonomy exclusions (Spadotto, 2006). The statistical result (Kruskal–Wallis test showing no significant difference) thus reinforces the need for effective impact metrics (like EIQ) and Monitoring, Reporting, and Verification (MRV) arrangements that capture real-world risk.

The findings suggest that establishing thresholds at percentiles (P85, P90, P95)—rather than fixed cutoffs—could introduce scientific objectivity and regulatory predictability, facilitating the gradual substitution of critical molecules and enabling linkages to fiscal and credit incentives.

This approach is analogous to the stochastic frontier model (Aigner et al., 1977; Coelli et al., 2005), which measures the deviation between observed performance and an efficient frontier. In the agro-environmental context, this frontier represents the maximum possible level of environmental efficiency for a given level of production. By identifying the upper percentiles of the EIQ distribution as high-impact outliers, the taxonomy approximates an environmental efficiency frontier, distinguishing between tolerable inefficiencies and critical ones.

Finally, the same reasoning can be extended to the conservation dimension: the LR surplus, distributed across percentiles (P70, P80, P90), can anchor progressive financial rewards, such as interest rate reductions, additional guarantees, and access to green credit lines. This would materialize the principle that sustainability occurs on a continuous spectrum, not as a binary state.

Formally, we it is proposed a dual frontier model:

$$S_i = f\left(X_i, \beta\right) - \delta_{EIQi} + \delta_{RLi} + \upsilon_i$$

Where penalties for input impact (EIQ) and bonuses for conservation (LR surplus) operate simultaneously. On this trajectory, properties advance toward the ideal frontier and are financially rewarded—including when LR surpluses up to 10% above the legal requirement are compensated and can be traded as CRA or CPR-Verde.

Therefore, this represents a hybrid model that aligns microeconomic efficiency with environmental macroeconomics, replacing generic prohibitions with calibrated incentives and offering a pragmatic regulatory pathway for sustainable taxonomy in Brazil.

5.2 Effective MRV system: agronomic prescriptions and a hybrid IPM-EIQ metric

Based on currently available documents, an MRV architecture anchored in agronomic prescriptions is recommended. Such a system would systematically record key parameters, including product brand, formulation, dosage, application frequency, mechanism of action, and the share of biological inputs used. These data can feed into a hybrid agro-environmental sustainability calculator (IPM-R), which scores management programs based on EIQ and IPM practices (Kovach et al., 1992; Obregon et al., 2025) and is designed to be accessible to technicians and rural producers.

Concurrently, the tool would integrate with public CAR databases to automatically assess the required LR percentage by biome and calculate the native vegetation surplus in percentage points above the legal minimum, applying differentiated weights and decay functions for the Amazon, Cerrado, and other biomes. From this information, the calculator would estimate a sustainability index according to the stochastic frontier model, where efficient input use and LR surplus shift the property toward the optimal frontier of environmental performance.

The results would present as a normalized score (0–100), with a "traffic light" visual dashboard classifying operations into green, yellow, or red zones based on their level of efficiency and financial eligibility. This approach, perhaps one of the most pragmatic for operationalizing the BST, reduces verification costs, discourages regulatory escape through product reformulation, and transforms technical-scientific parameters—such as EIQ and LR surplus—into objective criteria for green credit and certification, thereby reinforcing transparency and environmental education among producers and financial agents.

5.3 Policy design principles for an operational sustainable taxonomy

Environmental legality must be the starting point, not an exclusion criterion. Compliance with the Forest Code constitutes a minimum requirement for sustainability, but interpretations that conflate legal vegetation clearing with degradation must be avoided. The BST must recognize additionality, that is, practices exceeding legal obligations, such as maintaining a LR above the minimum, restoring degraded areas, and using biological inputs, thus converting them into assets eligible for financial incentives. This logic enables the integration of tradable instruments into the sustainable credit market, alongside other economic incentives like tax cashbacks.

The empirical analysis of the CAR database shows that approximately 9 million hectares of surplus vegetation—equivalent to a public asset without fiscal recognition—could be integrated into compensation mechanisms via tradable instruments like the CRA or the CPR-Verde.

5.4 Compatibility between science and regulation

The taxonomy must be grounded in scientific evidence and risk assessment, replacing inadequate normative classifications with internationally recognized metrics like the EIQ and input environmental efficiency indicators (Love et al., 2025). This integration reduces the gap between scientific and regulatory criteria, harmonizing IBAMA's Environmental Hazard Potential (PPA) with effective impact parameters. Using percentiles (P85, P90, P95) to distinguish high-impact substances enables risk calibration while maintaining coherence with IPM practices and the National Bioinputs Policy.

Similarly, this studyproposes that the LR be incorporated into the taxonomy not merely as a compliance requirement but as a positive, measurable, and compensable factor of environmental efficiency. Just as EIQ allows for identifying the risk tail associated with pesticide use, the distributional analysis of LR surpluses in percentage points above the legal minimum defined by biome can reveal the efficiency tail of conservation. In the proposed model, each percentage point of LR surplus is weighted by biome (20% for other regions, 35% for the Cerrado, and 80% for the Amazon), applying decay functions and maximum caps to avoid distortions. Thus, bonuses for LR surplus become a technical instrument for valuing conservation and also a territorial efficiency indicator, integrated into the stochastic sustainability frontier and the credit and green certification mechanisms foreseen by the BST.

5.5 Proportionality and focus on the risk tail

Effective policies concentrate on cases of high marginal impact, avoiding broad exclusions that affect the majority of sustainable operations. Percentile-based thresholds, rather than class-based prohibitions, allow for differentiating real risk from regulatory risk. Therefore, the BST should adopt a "narrow-tail" logic, prioritizing the mitigation or gradual substitution of the 10–15% of products with the highest impact without compromising agricultural competitiveness. This approach preserves the economic coherence of the transition, ensuring environmental efficiency without productivity loss (Möhring et al., 2019).

The "narrow-tail" logic should also guide the formulation of territorial incentives, especially in agricultural frontier areas where land-use conversion pressure is highest. Instead of adopting generalized restrictions, the taxonomy can direct graduated incentives to operations that, even when conducting legally authorized vegetation clearing (Vegetation Suppression Authorization—ASV), promote expanded environmental compensations. This means stimulating projects that reward the restoration or preservation of areas equivalent to more than 100% of the cleared area, creating net positive additionality in vegetation cover and resulting in net removals of greenhouse gas (GHG) emissions.

5.6 Integration of financial and fiscal instruments

Sustainability must be operationalized through incentive mechanisms, not just restrictions. Credit lines, guarantees, and interest rate equalizations can be modulated according to environmental performance, rewarding producers who reduce their EIQ or increase conserved area. In the fiscal domain, incentives similar to those proposed by Piñeiro et al. (2020) and Shukla et al. (2024)—such as tax reductions for bioinputs and low-emission technologies, or tax credits linked to certifications—can reinforce voluntary adherence to the BST. Convergence between financial instruments (credit, insurance, guarantees) and fiscal tools (exemptions, deductions, PSA) should form an integrated system of rewards for regenerative practices.

Consolidation of an effective incentive system depends on the robustness of MRV mechanisms and their integration with principles of financial and environmental accountability. The traceability and transparency of sustainable practices are essential conditions for recognizing environmental assets and preventing double counting or greenwashing. In this context, the BST could allow the stacking of economic instruments on the same LR or voluntary conservation area, provided the additionality of each operation is demonstrated. Thus, certified areas could simultaneously generate CRA, participate in REDD+ programs, issue CPR-Verde, and trade carbon credits in voluntary markets, if the benefits are proportional and auditable. This integration of environmental value layers creates synergies between public policies and private instruments, enabling a single area to contribute measurably to conservation, climate mitigation, and farmer remuneration. By articulating MRV, accountability, and instrument stacking, the BST becomes not just a normative classification, but an operational green finance system capable of channeling resources into effectively regenerative activities.

While the integration of financial and environmental instruments expands the potential for remunerating ecosystem services, it demands robust safeguards to prevent the double counting of environmental benefits—especially when areas are simultaneously eligible for CRA, REDD+, CPR-Verde, or voluntary carbon markets. The BST must ensure that each ton of CO_2 avoided, and each conserved hectare are counted only once. This requires univocal geospatial tracking, interoperability between public and private registries, and additional methodologies compatible with Article 6 of the Paris Agreement, the GHG Protocol, and ISO 14064. Under this logic, instrument stacking is not incompatible with carbon market principles, provided each layer represents a distinct, verifiable, and non-overlapping environmental benefit. By clearly differentiating conservation mechanisms (CRA), mitigation (REDD+), sustainable production (CPR-Verde), and carbon credits, the BST ensures accounting integrity, transparency, and international trust, allowing multiple incentives to coexist without compromising the system's environmental credibility.

5.7 Federative coherence and international interoperability

The BST must ensure full interoperability with international taxonomies, such as the European Union's Regulation 2020/852, harmonizing environmental indicators, terminology, and MRV methods with standards from the EU, OECD, and multilateral banks, without losing relevance to national conditions (Dusík and Bond, 2022; Inderst and Opp, 2025). Unlike what is suggested in the Brazilian draft, none of these taxonomies establishes direct restrictions on pesticide use or the toxicological classification of agricultural inputs as a financial exclusion criterion, focusing instead on emissions, resource efficiency, and biodiversity protection. In this context, imposing additional filters on Brazilian agriculture could create regulatory asymmetry, especially considering the country already operates under one of the world's most rigorous environmental frameworks, embodied in the Forest Code (Law 12.651/2012), which mandates specific LR percentages (20, 35, and 80%) and the protection of Permanent Preservation Areas. The integration of official data—such as CAR, PRODES, SICOR, and SNCR—is therefore essential to guarantee international comparability while reducing transaction costs and strengthening the BST's credibility.

Introducing normative additions to this system, such as automatic exclusions associated with pesticides or legal vegetation clearing, risks further restricting Brazilian agribusiness's comparative advantages, constituting a reverse Pigouvian effect on development. Instead of correcting negative externalities, such measures function as an implicit tax on formally sustainable production, penalizing agents who already internalize environmental costs and creating competitive distortions relative to countries operating under less restrictive frameworks (Davis et al., 2025).

5.8 Technical governance and evidence-based MRV

The BST's credibility depends on an MRV system that is robust, simple, and auditable. The digital agronomic prescription, coupled with a hybrid IPM-EIQ metric, provides a practical foundation for traceability and transparency (Kovach et al., 1992; Obregon et al., 2025). This arrangement allows technical data issued by agronomists and forestry engineers to support on-the-ground practice verification, replacing self-declarations. Furthermore, the participation of Embrapa, universities, and professional councils in technical governance strengthens the link between science and public policy, ensuring periodic updates to the taxonomy's criteria.

In this context, the "*Agro Brasil Mais Sustentável*" platform, developed under the Ministry of Agriculture and Livestock (MAPA), represents a strategic advance in integrating public policies, environmental data, and financial instruments. The tool aims to consolidate, in a single digital environment, information from official databases such as CAR, SIGEF, PRODES, DETER, and SICOR, enabling the automatic verification of territorial and environmental compliance. By cross-referencing data on deforestation, land cover, rural credit, and land tenure regularity, the platform provides objective evidence for risk assessment and BST eligibility classification.

However, its implementation requires overcoming technical and institutional challenges, such as system interoperability, geospatial data standardization, and the definition of confidentiality and governance protocols. Nonetheless, converging these databases into an integrated digital architecture is an essential step toward consolidating a national, evidence-based MRV system, enhancing the transparency, traceability, and credibility of Brazilian agricultural sustainability for investors and international partners.

5.9 Regulatory predictability and just transition

Finally, the BST must ensure transparency, gradual implementation, and a clear adaptation horizon for economic agents. The best example comes from the agroecological transition planned in organic farming certification models, which can involve periods of up to 5 years. Abrupt transitions undermine supply chain stability and deter investors. The adoption of 3 to 5-year transition plans, with gradual risk reduction targets and annual percentile reviews, will allow for the calibration of incentives, protection of rural jobs, and assurance of a just transition. Regulatory predictability is an essential condition for the BST to become an instrument of economic policy, not merely symbolic certification.

This logic makes sustainability a continuous, rather than binary, pursuit: properties advance toward the ideal frontier and are financially rewarded—including when LR surpluses up to 10% above the legal requirement are compensated and can be traded as CRA or CPR-Verde. This represents a hybrid model that aligns microeconomic efficiency with environmental macroeconomics, replacing generic prohibitions with calibrated incentives.

6 Conclusion

The empirical evidence indicates that the effectiveness of the BST depends on the use of measurable and comparable indicators of environmental risk and performance. Results show that exclusionary criteria based on toxicological hazard classes or on legally authorized vegetation clearing generate inconsistencies with observed data, as they would render ineligible a substantial share of production systems operating under IPM and in compliance with the Brazilian Forest Code.

Distributional analyses demonstrate that environmental impacts are highly concentrated: percentile thresholds applied to the EIQ isolate approximately 10–15% of high-impact cases, while preserving the operational viability of the remaining portfolios. Similarly, the spatial distribution of LR surplus reveals a significant stock of native vegetation that is legally protected under Brazilian law. Under the Brazilian Forest Code, a LR is the mandatory portion of a rural property that must be maintained with native vegetation, corresponding to a fixed percentage of the property area (ranging from 20 to 80%, depending on the biome and regional classification). Current estimates indicate that surplus areas amount approximately 19.2 million hectares nationwide—concentrated mainly in the Amazon and Cerrado biomes, with an estimated carbon value of BRL 579.7 billion at a reference price of BRL 75 per tCO_2.

Results further indicate that a graduated, percentile-based framework allows financial regulation to discriminate environmental risk without binary exclusions. Low EIQ percentiles combined with higher LR surplus correspond to lower-risk profiles, whereas the upper tail of the EIQ distribution concentrates disproportionate environmental impact, justifying targeted mitigation requirements. Credit–deforestation elasticities estimated at the state level show heterogeneous responses, including negative elasticities in several Cerrado states, indicating that increased sustainable credit does not systematically translate into higher deforestation.

These findings should be interpreted in light of data comparability constraints and the use of aggregate indicators, as well as the theoretical nature of carbon valuation estimates and potential endogeneity in credit–deforestation relationships. Nonetheless, they consistently support the conclusion that an operational taxonomy grounded in percentile-based metrics, legal compliance, and territorially differentiated indicators provides a coherent empirical basis for aligning rural credit, environmental performance, and financial risk management in the Brazilian context.

Author contributions

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

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

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 tools were used exclusively to support language editing, clarity, and organization of the text, including grammatical revision and improvement of academic writing style. All conceptual development, data analysis, interpretation of results, methodological design, and policy analysis were conducted by the author(s). No generative AI was used to generate original data, perform statistical analyses, or draw scientific conclusions.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1774282/full#supplementary-material

References

Aigner, D., Lovell, C. A. K., and Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models. *J. Econ.* 6, 21–37. doi: 10.1016/0304-4076(77)90052-5

Alvarenga Junior, M., and Young, C. E. F.. (2021). Princípios para a construção de uma macroeconomia pós-keynesiana do meio ambiente: revisitando Keynes em tempos de crises. Dossiê AKB-ECOECO: o desafio contemporâneo: construindo novas narrativas para a economia do meio ambiente e do clima. Available online at: http://hdl.handle.net/11422/20763 (Accessed March 15, 2025).

Assunção, J., Gandour, C., and Rocha, R. (2015). Deforestation Slowdown in the Brazilian Amazon: Prices or Policies? *Environment and Development Economics*, 20, 697–722. doi: 10.1017/S1355770X15000078

Assunção, J., Gandoura, C., Rochaa, R., and Rochab, R.. (2023). Does credit A ect deforestation? Evidence from a rural credit policy in the Brazilian Amazon. Climate Policy Initiative, Rio de Janeiro, Brasil. Available online at: https://climatepolicyinitiative.org/wp-content/uploads/2013/01/Does-Credit-Affect-Deforestation-Evidence-from-a-Rural-Credit-Policy-in-the-Brazilian-Amazon-Technical-Paper-English.pdf (Accessed April 10, 2025).

Banco Central do Brasil (2024). Crédito Rural. Available online at: https://www.bcb.gov.br/estabilidadefinanceira/creditorural (Accessed January 30, 2025).

Banerjee, A. V., and Duflo, E. (2012) Poor Economics: A radical Rethinking of the way to Fight Global Poverty London Hachette. Available online at: https://www.ceeol.com/search/article-detail?id=622820 (Accessed April 12, 2025).

Brasil (2012). Lei n° 12.651, de 25 de maio de 2012. Institui o novo Código Florestal Brasileiro. Available online at: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/L12651compilado.htm (Accessed November 30, 2025).

Brasil, Ministério da Ciência, Tecnologia e Inovações (2023). Relatório do Inventário Nacional das Emissões Antrópicas por Fontes e das Remoções por Sumidouros de Gases de Efeito Estufa. Brasília: MCTI. Available online at: https://www.gov.br/mcti/ (Accessed December 2, 2025).

Brasil, Ministério da Fazenda (2025). Taxonomia Sustentável Brasileira. Brasília: Ministério da Fazenda. Available online at: https://www.gov.br/fazenda/pt-br/orgaos/spe/taxonomia-sustentavel-brasileira (Accessed December 2, 2025).

Brazilian Institute of Environment and Renewable Natural Resources (2025). Sistema de Agrotóxicos – Consulta Pública de Ingredientes Ativos. Brasília: IBAMA. Available online at: https://www.gov.br/ibama/pt-br/assuntos/quimicos-e-biologicos/agrotoxicos (Accessed December 8, 2025).

Brock, R. C., Arnell, A., Simonson, W., Soterroni, A. C., Mosnier, A., Ramos, F., et al. (2021). Implementing Brazil's forest code: a vital contribution to securing forests and conserving biodiversity. *Biodivers. Conserv.* 30, 1621–1635. doi: 10.1007/s10531-021-02159-x

Coelli, T. J., Prasada Rao, D. S., O'donnell, C. J., and Battese, G. E. (2005). *An Introduction to Efficiency and Productivity Analysis*. Boston, MA: Springer US.

Davis, E. C., Ivanic, M., and Sohngen, B. (2025). Avoiding global deforestation by taxing land in agricultural production: the implications for global markets. *Carbon Balance Manag.* 20:5. doi: 10.1186/s13021-025-00291-7

Dusík, J., and Bond, A. (2022). Environmental assessments and sustainable finance frameworks: will the EU taxonomy change the mindset over the contribution of EIA to sustainable development? *Impact Assess. Proj. Apprais.* 40, 90–98. doi: 10.1080/14615517.2022.2027609

European Commission (2025). EU Pesticides Database – Active Substances. Brussels: Directorate-General for Health and Food Safety. Available online at: https://food.ec.europa.eu/plants/pesticides/eu-pesticides-database_en (Accessed December 8, 2025).

Eyhorn, F., Muller, A., Reganold, J. P., Frison, E., Herren, H. R., Luttikholt, L., et al. (2019). Sustainability in global agriculture driven by organic farming. *Nat. Sustain.* 2, 253–255. doi: 10.1038/s41893-019-0266-6

FAO (2022) FAOSTAT Analytical: Pesticides use, pesticides trade and pesticides indicators Rome Food and Agriculture Organization. Available online at: https://openknowledge.fao.org/handle/20.500.14283/cc0918en (Accessed November 12, 2025).

Food and Agricultural Materials Inspection Center (2025). List of Active Ingredients of Registered Agricultural Chemicals under the Agricultural Chemical Regulation Act (Act No. 82 of July 1, 1948). Tokyo: FAMIC. Available online at: https://www.acis.famic.go.jp/eng/ailist/ (Accessed December 8, 2025).

Grossman, G. M., and Krueger, A. B. (1995). Economic growth and the environment. *Q. J. Econ.* 110, 353–377. doi: 10.2307/2118443

Hungria, M., and Nogueira, M. A. (2022). Fixação biológica do nitrogênio. In: M. C. Meyer, A. F. Bueno, S. M. Mazaro and J. C. Silva (eds.) Bioinsumos na cultura da soja. Brasília: Embrapa, 141–162. Available online at: http://www.alice.cnptia.embrapa.br/alice/handle/doc/1143066 (Accessed December 2, 2025).

IBAMA (2025) Pesticide commercialization reports. Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). Available online at: https://www.gov.br/ibama/pt-br/assuntos/quimicos-e-biologicos/agrotoxicos/relatorios-de-comercializacao-de-agrotoxicos (Accessed November 20, 2025).

Inderst, R., and Opp, M. M. (2025). Sustainable finance versus environmental policy: does greenwashing justify a taxonomy for sustainable investments? *J. Financ. Econ.* 163:103954. doi: 10.1016/j.jfineco.2024.103954

Instituto Nacional de Pesquisas Espaciais (2024). PRODES: Monitoramento Anual da Supressão de Vegetação Nativa no Brasil. Available online at: https://data.inpe.br/biomasbr/prodes-monitoramento-anual-da-supressao-de-vegetacao-nativa/ (Accessed January 30, 2025).

Kassam, A. (2023). "Conservation agriculture for regenerative and resilient production systems," in *Biological Approaches to Regenerative Soil Systems*, (Boca Raton: CRC Press), 251–264.

Kovach, J., Petzoldt, C., Degni, J., and Tette, J. (1992) A method to measure the environmental impact of pesticides N. Y. Food Life Sci. Bull. 139 1–8 Available online at: http://hdl.handle.net/1813/55750 (Accessed July 10, 2025).

Lima, M. G. (2024). Crédito de carbono: análise do mercado brasileiro. *Rev. Tecnol. FATEC* 15. doi: 10.62790/rtfv15n2-002

Love, M., Magarey, R. D., Holdermon, B. L., Carley, D. S., Maggi, F., and Singer, N. (2025). Tracking sustainability in crop pest management in the United States using an eco-efficiency index. *Front. Insect Sci.* 5:1582496. doi: 10.3389/finsc.2025.1582496

Maia, S. M. F., Medeiros, A. S., Santos, T. C., Lyra, G. B., Lal, R., Assad, E. D., et al. (2022). Potential of no-till agriculture as a nature-based solution for climate-change mitigation in Brazil. *Soil Tillage Res.* 220:105368. doi: 10.1016/j.still.2022.105368

May, P. H., Bernasconi, P., Wunder, S., and Lubowski, R. (2016). *Cotas de reserva ambiental no novo Código Florestal brasileiro: uma avaliação ex-ante*. Bogor: CIFOR.

Möhring, N., Gaba, S., and Finger, R. (2019). Quantity-based indicators fail to identify extreme pesticide risks. *Nat. Plants* 5, 1029–1038. doi: 10.1016/j.scitotenv.2018.07.287

Monteiro, A., Barreto-Mendes, L., Fanchone, A., Morgavi, D. P., Pedreira, B. C., Magalhães, C. A. S., et al. (2024). Crop-livestock-forestry systems as a strategy for mitigating greenhouse gas emissions and enhancing the sustainability of forage-based livestock systems in the Amazon biome. *Sci. Total Environ.* 906:167396. doi: 10.1016/j.scitotenv.2023.167396

Nascimento, E. L. M., Velazco, S. J. E., Ramos, F. M., Ramos, R. G., Soterroni, A. C., and Tessarolo, G. (2025). Climate change and feeble governance threaten the endangered endemic Cerrado flora in Brazil. *Perspect. Ecol. Conserv.* 23, 290–299. doi: 10.1016/j.pecon.2025.08.007

Nogueira, J. M., Conceição, P. H. Z., and Imbroisi, D. (2015) Crédito bancário, risco ambiental e sustentabilidade empresarial: o caminho percorrido pelas instituições financeiras no Brasil Bus. Manag. Rev. 4 734–744. Available online at: https://www.engema.org.br/XVIENGEMA/345.pdf (Accessed September 5, 2025).

Nwaogu, C., Oti, N. N., Enaruvbe, G. O., and Cherubin, M. R. (2024). "Crop-livestock-forest system as nature-based solutions to combating climate change and achieving SDGs in Brazil," in *Handbook of Nature-Based Solutions to Mitigation and Adaptation to Climate Change*, eds. W. Leal Filho, G. J. Nagy and D. Y. Ayal (Cham: Springer).

Obregon, D., Hernandez Correal, D., Eshenaur, B., and Calixto, A. A. (2025). Global use of the environmental impact quotient. *Sci. Total Environ.* 997:180235. doi: 10.1016/j.scitotenv.2025.180235

Oliveira, E. (2017). Economia Verde, economia ecológica e economia ambiental: uma revisão. *Rev. Meio Ambiente e Sustentab.* 13:2071. doi: 10.22292/mas.v13i6.751

Oliveira, D. M. S., Tavares, R. L. M., Loss, A., Madari, B. E., Cerri, C. E. P., Alves, B. J. R., et al. (2023). Climate-smart agriculture and soil C sequestration in Brazilian Cerrado: a systematic review. *Rev. Bras. Ciênc. Solo* 47:e0220055. doi: 10.36783/18069657rbcs20220055

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nat. Sustain.* 3, 809–820. doi: 10.1038/s41893-020-00617-y

Reis, J. C., Kamoi, M. Y. T., Tanure, T. M. P., Rodrigues, M. I., Etienne, J. J. D., Valentim, J. F., et al. (2025). Integrated crop-livestock-forest systems: a path to improved agro-economic performance in the Brazilian Amazon and Cerrado. *Front. Sustain. Food Syst.* 9:1518747. doi: 10.3389/fsufs.2025.1518747

Sá, J. C. M., Lal, R., Lorenz, K., Bajgai, Y., Gavilan, C., Kapoor, M., et al. (2025). No-till systems restore soil organic carbon stock in Brazilian biomes and contribute to the climate solution. *Sci. Total Environ.* 977:179370. doi: 10.1016/j.scitotenv.2025.179370

Schütze, F., and Stede, J. (2024). The EU sustainable finance taxonomy and its contribution to climate neutrality. *J. Sustain. Financ. Invest.* 14, 128–160. doi: 10.1080/20430795.2021.2006129

Serviço Florestal Brasileiro (SFB) (2024). Sistema Nacional de Cadastro Ambiental Rural (SICAR). Available online at: https://consulta.car.gov.br/ (Accessed May 16, 2025).

Shukla, P., Taneja, B., and Sahin, C. (2024). "Green finance: tax incentives, challenges, and future potential," in *Modern Concepts and Practices of Climate Finance*, (ed.) A. Rafay, (Hershey: IGI Global), 155–184.

Spadotto, C. A. (2006). Avaliação de riscos ambientais de agrotóxicos em condições brasileiras. Jaguariúna: Embrapa Meio Ambiente. Available online at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/15967 (Accessed December 2, 2025).

Telles, T. S., Nogueira, M. A., and Hungria, M. (2023). Economic value of biological nitrogen fixation in soybean crops in Brazil. *Environ. Technol. Innov.* 31:103158. doi: 10.1016/j.eti.2023.103158

United States Environmental Protection Agency (2025). Pesticide Product and Label System (PPLS) – Registered Pesticide Products. Washington, D.C.: U.S. EPA. Available online at: https://www.epa.gov/pesticide-registration (Accessed December 8, 2025).