Macrothink Institute™

Environmental Management and Sustainable Development
ISSN 2164-7682
2025, Vol. 14, No. 2

Pressure over Stock: Explaining REDD+ Siting and Management in Brazil

Thiago Gil

FGV EAESP, Brazil

Wesley Mendes da Silva

FGV EAESP, Brazil

Received: August 28, 2025 Accepted: October 6, 2025 Published: October 15, 2025

doi:10.5296/emsd.v14i2.23115 URL: https://doi.org/10.5296/emsd.v14i2.23115

Abstract

The Amazon remains a climate cornerstone, yet deforestation pressures persist and the role of carbon projects in mitigating those pressures is contested. We assemble a municipality-level panel for the Brazilian Amazon by harmonizing land-cover classifications, deforestation indicators, municipal geometries, and the Verified Carbon Standard (VCS) registry of REDD+ projects. Spatial structure is characterized with Moran's I and Local Indicators of Spatial Association (LISA); environmental profiles are synthesized via PCA-assisted hierarchical clustering. To explain where projects occur, we estimate standard and Firth bias-reduced logistic regressions with standardized predictors reflecting pressure (recent deforestation) and stock (remaining forest cover). Projects concentrate both in well-preserved forest clusters and along livestock/agriculture conversion frontiers, indicating a bimodal geography consistent with preventive and reactive logics. Across specifications, recent deforestation share is the only consistent, statistically significant predictor of siting; a one-standard-deviation increase raises the odds of REDD+ presence by about 50% (OR ≈ 1.5) in the Firth model, while simple "more forest, more projects" patterns weaken once recent clearing is controlled for. We discuss implications for interpreting siting through a transparent pressure-stock lens (as an interpretive, not prescriptive, tool), and we note limitations alongside extensions using spatial logit/probit, improved entity resolution, and quasi-experimental checks for impacts.

Keywords: Carbon credits, Amazon, Deforestation, Sustainable finance

1. Introduction

The Brazilian Amazon is simultaneously a carbon reservoir, a biodiversity stronghold, and a frontier of rapid land-use change. Recurrent policy cycles and commodity booms have produced alternating phases of control and acceleration in deforestation, renewing calls for scalable mechanisms that can finance conservation where pressure is greatest. REDD+ projects promise exactly that: pay to avoid emissions from deforestation and degradation. Yet persistent debates about additionality, leakage, and targeting have left a fundamental empirical question insufficiently answered: where do projects actually go relative to deforestation risk and remaining forest stock, and how does that placement relate to reported emissions reductions?

This paper tackles that question by integrating high-resolution environmental data with project registries at the scale of Brazilian municipalities. We study where REDD+ projects are sited (descriptive) and why (interpretive), using a national, municipality-level panel with explicit spatial diagnostics. Unlike prior basin-wide deforestation risk maps, our focus is the siting logic itself, interpreting choices through a pressure-versus-stock lens tied to conservation targeting and additionality. We show that recent deforestation pressure - not forest stock - robustly predicts siting in bias-reduced logit, with a bimodal geography (core forests vs frontiers). We discuss implications for leakage risk, programmatic targeting, and voluntary market credibility.

The data strategy encompasses IBGE municipality geometries with MapBiomas land-cover shares and INPE/PRODES indicators of total and recent deforestation, then match those units to Verra's Verified Carbon Standard (VCS) records of REDD+ projects and annual emissions reductions. Because project presence is sparse, we adopt a rare-events estimation strategy (Firth logistic regression) alongside a standard logit, and we study the intensive margin via OLS on emission reductions from REDD+ projects. To interpret spatial structure rather than treat it as noise, we quantify global and local spatial dependence (Moran's I, LISA) and summarize multivariate land-use environments with PCA-assisted hierarchical clustering. All predictors are standardized, enabling effect-size comparability.

This problem matters because climate finance only works if capital reaches places where additionality is plausibly highest—i.e., where governance is thin and deforestation pressure is acute (Hänggli et al., 2023; Coelho & De Toledo, 2024). We extend prior work on Amazon drivers (Busch & Ferretti-Gallon, 2017), conservation targeting, and REDD+ evaluation (Duchelle et al., 2014; Griscom et al., 2022) by pivoting from impact claims to the siting logic itself, using a harmonized Brazil-wide dataset and rare-events estimation with explicit spatial diagnostics—going beyond earlier case studies.

Our empirical strategy tests two claims derived from a pressure-stock perspective. H1 (targeting risk): municipalities with higher recent deforestation should have higher odds of project siting, where additionality is plausibly greater. H2 (remaining stock): greater forest cover should increase siting odds by enlarging the pool of avoidable emissions. We investigate these hypotheses by analyzing geographical clusters and by including standardized predictors for recent deforestation ("pressure") and forest cover ("stock") in MLE/Firth logistic models of project presence. We deliberately do not test an "intensive margin" because reported emission reductions are project-level outcomes that are endogenous to siting and project design.

Despite decades of research, evidence on voluntary REDD+ remains mixed—some studies find real avoided deforestation (global evaluation: Guízar-Coutiño et al., 2022; Brazil project-level evidence: Simonet et al., 2019; national program evidence: Roopsind et al., 2019), while others flag baseline inflation and over-crediting in Brazilian voluntary projects (West et al., 2020; West et al., 2023). What's missing is a Brazil-wide, spatially explicit test of whether projects track recent clearing ("pressure") and/or protectable forest ("stock") once spatial dependence is accounted for. This matters both theoretically (pressure-stock targeting) and practically (allocating scarce climate-finance and strengthening MRV).

The results are clear on H1: recent deforestation share is the only predictor that robustly and significantly explains siting across logistic specifications. H2—the idea that "more forest implies more projects"—receives limited support once recent clearing is controlled for. Spatial diagnostics indicate a bimodal geography: projects cluster in high-integrity forest areas and along livestock-conversion frontiers, a pattern with implications for leakage risk, monitoring costs, and verification. Because project-reported reductions are endogenous to siting choices, we treat any associations between pressure/stock and reported volumes as descriptive context only and refrain from inference on intensity.

This paper contributes on three fronts. Substantively, it provides spatially explicit evidence that REDD+ is preferentially sited where recent clearing is elevated, aligning with an additionality-oriented targeting narrative rather than uniform dispersal. Methodologically, it combines rare-events logit with explicit spatial diagnostics and multivariate clustering to interpret placement under spatial dependence and data sparsity. Practically, while we do not implement a prioritization exercise, the estimated siting relationships can be read ex post through a simple, auditable pressure-stock lens that may inform future program design and MRV. We also note limitations relevant for inference and policy: name-based municipality matching may understate presence in some treated places, and residual spatial dependence could affect standard errors; both are tractable with improved entity resolution and spatial econometrics.

We invoke a management perspective strictly as a conceptual guide rather than a prescriptive rule. The pressure-stock lens structures testable predictions and aids interpretation of siting coefficients; it does not determine allocations in our analysis. Nonetheless, because the inputs come from routine monitoring, the same lens could inform future procurement pipelines and comparative assessments of siting strategies without altering the empirical claims tested here.

The remainder proceeds as follows. Sub-section 1.2 situates the study within literatures on Amazon deforestation, conservation targeting, and REDD+ evaluation. Section 2 details data construction, spatial harmonization, and the statistical framework. Section 3 presents spatial diagnostics and clustering. Section 4 reports siting results vis-à-vis H1-H2 and discusses endogeneity concerns surrounding project-reported reductions. Section 5 considers policy implications, robustness, and avenues to address endogeneity in future work.

1.1 Literature Review

As the world's largest tropical rainforest, the Amazon stores approximately 150-200 billion tons of carbon—equivalent to 15-20 years of global CO_2 emissions—making it one of the planet's most important carbon reservoirs (Flores et al. 2024). The forest spans over 5.5 million km2 across nine countries and contains more than 10% of Earth's terrestrial biodiversity (Ellwanger et al. 2020). However, the Amazon had already lost approximately 900,000 km^2 of its original forest cover, primarily due to agricultural expansion, cattle ranching, and infrastructure development, with deforestation rates directly linked to global economic drivers, including demand for soybeans and international commodity prices (Lapola et al. 2023). The implications extend beyond regional boundaries: deforestation causes substantial warming up to 100 kilometers away from forest loss sites, contributes 3% of global net carbon emissions annually, and affects precipitation patterns across South America (Butt et al. 2023).

Current projections under business-as-usual scenarios indicate that 10-47% of Amazonian forests will be exposed to compounding disturbances by 2050, potentially triggering irreversible ecosystem transitions that would transform this critical carbon sink into a major source of atmospheric carbon, thereby accelerating global climate change and threatening the achievement of international climate targets (Flores et al. 2024).

Amazon deforestation has an economic component shaped by commodity cycles and governance. Across three decades of research, cattle ranching dominates forest conversion, responsible for ~68% of the phenomenon, with soybean expansion acting as the second force (Busch & Ferretti-Gallon, 2017; Hänggli et al., 2023). Beyond simple market trends, part of the literature underscores that deforestation surges where environmental governance weakens (Hänggli et al., 2023; Coelho & De Toledo, 2024), creating a dichotomy of market and governance forces.

A clear temporal arc underpins these outcomes. After very high clearing (1988-2004), the PPCDAm policy package plus satellite enforcement drove steep declines in deforestation (2004-2012), before policy cuts eroded efforts (Prates & Bacha, 2011; Young, 1998; Benevides & Almeida, 2015; Correia-Silva & Rodrigues, 2019). Evidence consistently links enforcement intensity to lower deforestation, stressing the need for stable institutions and budgets (Correia-Silva & Rodrigues, 2019).

Even after decades of deforestation, cattle ranching remains the pivotal driver of forest cover change (Oliveira Junior et al., 2024). Soybeans act both directly and indirectly as a secondary driver: mechanized agriculture expands where terrain and soils allow, but a key channel is pasture displacement: soy occupies cleared pastures, pushing cattle deeper into forest margins (Jakimow et al., 2023). Global demand—especially EU/Asia feed markets—amplifies pressure against this moving agricultural frontier; new trade rules (e.g., EU deforestation-free regulation) could alter incentives but face implementation challenges (Lopes et al., 2023).

Other economic activities present spatially distinct footprints. Mining generates direct clearing and larger infrastructure multipliers (roads, transmission, processing), catalyzing additional forest losses (Herrera & Moreira, 2013). Timber extraction—legal and illegal—both degrades and changes forests for conversion; even intensified non-timber management can shift species composition and open pathways to clearing (Neves & Bizawu, 2019; Freitas et al., 2021; Giatti et al., 2021).

Despite these trends, monitoring and deterrence capacity evolved markedly. PRODES/INPE's annual mapping, complemented by near-real-time alerts and object-based classification, enabled targeted enforcement and accountability (Conceição et al., 2020). AI-assisted alerting improves precision and speed, yet actors adapt to evade detection, making sustained field enforcement indispensable (Dittmar & Mrozinski, 2022; Correia-Silva & Rodrigues, 2019).

Market instruments complement command-and-control but are not silver bullets. The Amazon Fund (a public fund managed by the Brazilian Development Bank (BNDES), created to raise and channel international donations for non-reimbursable investments in the Amazon), zero-deforestation supply-chain commitments, Payment for Environmental Services (PES), carbon credit projects, and trade measures can realign incentives, provided monitoring is credible and political support endures (Miyamoto, 2020; Lopes et al., 2023). Effectiveness hinges on coverage (avoiding leakage), verification, and stable financing.

REDD+ (Reducing Emissions from Deforestation and forest Degradation) projects have emerged as critical mechanisms for climate change mitigation in the Brazilian Amazon, representing one of the most significant forest conservation initiatives globally. Duchelle et al. (2014) demonstrate that REDD+ initiatives in the Brazilian Amazon have promoted important changes in institutional capacity, funding possibilities, and civil society mobilization, bringing unprecedented visibility to the importance of combating deforestation and forest degradation.

The Amazon Fund, established in 2008 as the world's largest REDD+ program, exemplifies this importance by channeling over $1.3 billion in results-based funding from Norway and Germany to reward Brazil for deforestation reductions (Börner et al. 2019). Global evaluations have shown that REDD+ projects can achieve meaningful conservation outcomes, with studies indicating that voluntary REDD+ projects reduced deforestation by 47% and forest degradation by 58% in their first five years compared to matched control areas (Griscom et al. 2022). These projects are particularly significant given that the Amazon contains approximately 60% of the world's remaining tropical forests and that deforestation contributes 10-35% of global carbon emissions (Sunderlin et al. 2014).

Despite their importance, REDD+ projects in the Amazon face substantial criticisms regarding their effectiveness and environmental integrity. Evidence splits across project- and program-level evaluations: matched pixel analyses report sizable within-project reductions in deforestation and degradation (Guízar-Coutiño et al., 2022). Another Brazil micro-level DID/DID-matching study finds roughly 50% lower clearing on participating farms (Simonet et al., 2019), and a synthetic-control assessment of a national REDD+ program shows meaningful tree-cover loss reductions during implementation with some post-program fade-out (Roopsind et al., 2019). In contrast, project-level synthetic controls for Brazilian voluntary projects suggest inflated baselines and no robust mitigation signal relative to counterfactuals (West et al., 2020), and subsequent methodological work argues that baseline construction is often unstable, risking over-crediting without tighter standards (West, Bomfim, & Haya, 2024). The mixed findings challenge the environmental integrity of carbon offset markets and suggests that many REDD+ projects have been claiming credit for deforestation reductions that resulted from broader national policies rather than project-specific interventions.

In addition, the social dimensions of REDD+ projects have generated considerable academic criticism, particularly regarding indigenous communities and local participation. Research by indigenous rights organizations has highlighted that REDD+ projects often fail to adequately implement Free, Prior and Informed Consent (FPIC) procedures, with studies showing that only one-third of households in project areas had sufficient information to accurately describe REDD+ initiatives affecting their territories (Cromberg et al. 2014). The Suruí Carbon Project, one of the first voluntary REDD+ interventions in an indigenous territory, exemplifies these challenges, as it was unable to prevent illegal logging and mining invasions despite international attention and carbon financing (West et al. 2020).

Critics argue that REDD+ governance structures prioritize efficiency over social justice, with limited meaningful participation of traditional communities in decision-making processes (May et al. 2011). Furthermore, studies reveal that REDD+ projects can exacerbate internal conflicts within communities, particularly regarding the distribution of carbon payments, while failing to strengthen local institutional capacity for forest management (Sills et al. 2022). Sunderlin et al. (2014) identify that tenure insecurity remains a critical barrier, as projects cannot effectively establish performance-based reward systems without clear identification of rights holders and responsible parties for forest conservation outcomes. Additionally, funding does not systematically target municipalities with the highest deforestation rates, and many governmental organizations lack financial additionality for their projects (Börner et al. 2019) while facing coordination and implementation barriers (Gebara, 2014).

Some of the REDD+ projects are private-owned and voluntary. They operate through market-based mechanisms that transform forest conservation into a commercially viable commodity by creating tradeable carbon credits for avoided deforestation. This approach is grounded in Payment for Ecosystem Services (PES) frameworks that compensate forest conservation based on opportunity cost calculations—the foregone economic benefits from not converting forests to agriculture (Silva, 2019. Van der Hoff et al. (2015) explain that this process "commodifies" emission reductions by detaching carbon from its local socio-environmental context and transforming it into globally tradeable units through certification mechanisms like Verra's Verified Carbon Standard.

This study examines the spatial distribution and economic contexts of REDD+ projects through a managerial pressure-stock lens. Specifically, we ask whether projects are preferentially sited in municipalities with high near-term deforestation pressure (recent clearing, fire/alert intensity, frontier access) and whether siting covaries with protectable forest stock (remaining cover, biomass, connectivity), net of regional economic forces such as soybean expansion, cattle ranching, and infrastructure. Our aim is not to prescribe or evaluate an allocation rule nor to infer project impacts; rather, we use this lens to organize falsifiable hypotheses about siting under scarcity and to interpret observed patterns within the conservation-targeting and land-use literatures. In line with endogeneity concerns around project-reported outcomes, we do not test an intensive margin of “emission reductions,” treating those quantities as descriptive context rather than causal evidence.

A growing strand of work uses spatial statistics to monitor and evaluate ecological interventions. Rodrigues et al. (2025) exemplifiy this approach by applying Moran’s I and LISA to map statistically significant deforestation clusters and relate them to cattle and crop expansion—evidence that can directly prioritize surveillance, audits, and project siting. In dialogue with broader Amazon evidence, these cluster-based diagnostics align with meta-analytic drivers of clearing (Busch & Ferretti-Gallon, 2017), governance-cycle effects on risk (Hänggli et al., 2023), and frontier dynamics in Southwest Pará (Jakimow et al., 2023), while also speaking to leakage risks along cattle supply chains (Oliveira Junior et al., 2024) and long-run development-deforestation linkages (Prates & Bacha, 2011; Young, 1998).

2. Method

This study integrates multiple geospatial datasets to analyze the environmental characteristics and spatial distribution of REDD+ projects across Brazilian Amazon municipalities. Land use and land cover data were obtained from the MapBiomas Collection 8.0 (1985-2022), providing annual classifications at 30-meter resolution for 23 land cover classes following the IBGE technical manual. Deforestation data were sourced from the PRODES (Amazon Deforestation Monitoring Program) database maintained by Brazil's National Institute for Space Research (INPE), offering official annual deforestation measurements since 1988. Municipal boundary geometries were obtained from the Brazilian Institute of Geography and Statistics (IBGE) 2024 official cartographic base. REDD+ project data were compiled from the Verified Carbon Standard (VCS) registry, encompassing 26 registered projects with verified emission reduction commitments.

2.1 Geospatial Analysis

All datasets were harmonized to the municipality level using zonal statistics, with land cover percentages calculated as the proportion of each class relative to total municipal area. PRODES variables were standardized following MapBiomas nomenclature conventions: Total Deforestation (%), Recent Deforestation (%), and Forest Remnants (%) to ensure methodological consistency. Spatial data processing was conducted using Python's GeoPandas library with coordinate reference system standardization to EPSG:4326 (WGS84).

Spatial autocorrelation patterns were assessed using Moran's I statistic to identify clustering tendencies in environmental variables. The global Moran's I is defined as:

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} * \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (1)$$

where n is the number of spatial units, x_i and x_j are observations at locations i and j, $\bar{x}$ is the sample mean, and w_{ij} represents spatial weights. Spatial weights were constructed using Queen contiguity (first-order neighbors sharing vertices or edges), with row-standardization applied ($\sum_j w_{ij} = 1$).

Local spatial autocorrelation was evaluated through Local Indicators of Spatial Association (LISA), calculating local Moran's I for each municipality:

$$I_i = \frac{(x_i - \bar{x})}{S^2} * \sum_{j=1}^{n} w_{ij}(x_j - \bar{x}) \tag{2}$$

Where $S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$. LISA analysis identifies four spatial association patterns: High-High (HH) clusters indicating hotspots, Low-Low (LL) clusters representing coldspots, and High-Low (HL) or Low-High (LH) outliers representing spatial anomalies. Statistical significance was assessed through conditional permutation tests (999 iterations) with $\alpha = 0.05$.

A clustering framework was implemented using Hierarchical Clustering to identify municipalities with similar environmental profiles. Prior to clustering, variables underwent standardization using z-score normalization. Dimensionality reduction was performed using Principal Component Analysis (PCA) to address multicollinearity and computational efficiency.

To perform Hierarchical Clustering, Ward's minimum variance method was applied to PCA-transformed data, minimizing within-cluster sum of squares:

$$\Delta(A, B) = \frac{|B|}{|A| + |B|} * \left|\left|\mu_A - \mu_B\right|\right|^2 \tag{3}$$

where |A| and |B| denote cluster sizes and μ_A, μ_B represent cluster centroids. Optimal cluster number was determined using the elbow method based on within-cluster sum of squares reduction.

REDD+ project locations were geocoded to municipal centroids and integrated with environmental cluster classifications. Projects were aggregated by municipality, with total annual emission reductions calculated as the sum of individual project contributions. Marker size scaling for visualization employed logarithmic transformation to accommodate the wide range of emission reduction values.

Cluster validity was assessed through multiple metrics including silhouette analysis, within-cluster sum of squares, and spatial autocorrelation of cluster assignments. The spatial structure of clustering solutions was evaluated using Moran's I on cluster membership, testing whether similar environmental conditions exhibit spatial clustering.

2.2 Regressions

As an additional test to identify the environmental and geographic factors associated with REDD+ project placement in Brazilian Amazon municipalities, we employed Firth logistic regression to address the rare events problem inherent in our dataset (19 REDD+ municipalities out of 774 total observations, representing 2.5% prevalence). The Firth correction provides bias-reduced maximum likelihood estimates specifically designed for binary outcomes with small sample sizes (Firth, 1993). Our dependent variable was binary, coded as 1 if a municipality contained at least one registered REDD+ project and 0 otherwise.

The model incorporated additional environmental variables from MapBiomas land use classification and PRODES deforestation monitoring, selected using correlation-based variable selection to prevent overfitting given our small positive case sample. The general form of our logistic regression model can be expressed as:

$$P(REDD+_i = 1) = \beta_0 + \beta_1 * Lat_i + \beta_2 * Lon_i + \sum_{j=3}^{k} \beta_j X_{ij} + \varepsilon_i \quad (4)$$

where $P(REDD+_i = 1)$ represents the probability that municipality i contains a REDD+ project, X_{ij} are standardized (z-score) municipal covariates. Covariates include PRODES pressure measures (recent and total deforestation shares), stock measures (forest share), and MapBiomas land-use shares (forest, savanna, pasture, soybean, wetland); latitude and longitude of the municipal centroid are added as broad spatial-trend controls. Predictors were retained when nationally available and informative (present in the dataset with variability, i.e., SD > 0.1), with basic collinearity screening, and parsimony enforced for a rare-events setting—limiting the final set to respect events-per-variable guidance (one predictor per ~3 positive cases).

Municipal aggregation is warranted because municipalities constitute the operative locus of land-use governance and REDD+ categorization in Brazil, while intra-unit heterogeneity is attenuated by employing scale-invariant covariates (shares/densities), incorporating broad spatial-trend controls, and conducting spatially robust inference.

Additionally, we consider another dependent variable: continuous annual emissions reduction (log-transformed to handle the preponderance of zero values). This dual approach allowed examination of both factors influencing REDD+ project placement and factors affecting emissions reduction magnitude.

All continuous predictors were standardized (mean = 0, standard deviation = 1) to facilitate coefficient interpretation and comparison. Missing values were handled through listwise deletion. Model convergence was ensured through increased iteration limits (2,000 maximum iterations) and reduced step sizes for the Firth regression.

Model diagnostics included assessment of separation issues, convergence status, and comparison of coefficient stability between standard and Firth approaches. Pseudo R^2 (McFadden) was calculated to assess model fit for logistic regressions, while adjusted R^2 was reported for ordinary least squares models.

3. Results

The LISA analysis reveals pronounced spatial clustering across all analyzed variables, with Moran's I values ranging from 0.611 to 0.895, indicating strong regional differentiation in land-use patterns across the Amazon. Agricultural variables demonstrate the most distinct spatial organization, with soybean cultivation (I=0.731) and pasture systems (I=0.825) exhibiting clear High-High clusters concentrated in the eastern and southern regions, corresponding to the established agricultural frontiers of Mato Grosso. Conversely, natural vegetation variables show complementary patterns, with forest formation (I=0.664) and floodable forests (I=0.789) displaying High-High clusters predominantly in the western and northern Amazon, representing the intact forest core. The savanna formation variable exhibits the strongest spatial autocorrelation (I=0.895), with High-High clusters clearly delineating the Cerrado-Amazon transition zone in the southeast, highlighting the distinct biogeographical boundaries that influence land-use trajectories.

REDD+ project distribution demonstrates strategic positioning relative to these spatial clusters, with most projects located within Low-Low clusters for agricultural variables and High-High clusters for forest variables, indicating appropriate targeting of well-preserved forest areas with minimal agricultural pressure. However, the recent deforestation analysis (I=0.638) reveals several REDD+ projects positioned within or adjacent to High-High deforestation clusters, particularly in central Rondônia and southern Amazonas. This spatial coincidence between REDD+ projects and active deforestation hotspots suggests strategic intervention in critical areas. The absence of REDD+ projects in the southeastern Cerrado transition zones (savanna High-High clusters) represents a notable gap, as these areas face significant conversion pressure but lack international climate financing mechanisms, potentially displacing deforestation pressure from REDD+ areas to unprotected transition landscapes.

The hierarchical clustering exercise shows that Cluster 1 represents the most well-preserved areas in the Amazon, encompassing 175 municipalities characterized by exceptional forest conservation. These areas maintain 72.9% forest formation coverage with 72.5% forest remnants, indicating minimal historical disturbance and high ecological integrity. Despite some historical deforestation (20.4%), these municipalities demonstrate low recent deforestation pressure (1.6%) and limited agricultural conversion, with pasture covering only 13.8% of the territory. This cluster represents prime areas for preventive conservation strategies, where REDD+ projects can focus on maintaining existing forest cover and supporting sustainable forest-based economies. The high forest remnants and low anthropic pressure make these areas ideal for long-term carbon storage and biodiversity conservation initiatives.

Cluster 5 represents an intensive agricultural conversion zone. The largest cluster (in city-count) comprises 285 municipalities experiencing the most severe deforestation pressure, with 72.5% total historical deforestation and 55.5% pasture coverage. These areas represent the epicenter of Amazon agricultural conversion, where extensive livestock farming has become the dominant land use following forest clearing. Despite significant forest loss, these municipalities still maintain 29.6% forest formation, presenting critical opportunities for REDD+ interventions to prevent further conversion of remaining forest patches. The high deforestation rates combined with substantial remaining forest coverage make this cluster a priority for urgent conservation action, where REDD+ projects must compete directly with strong economic incentives for continued agricultural expansion.

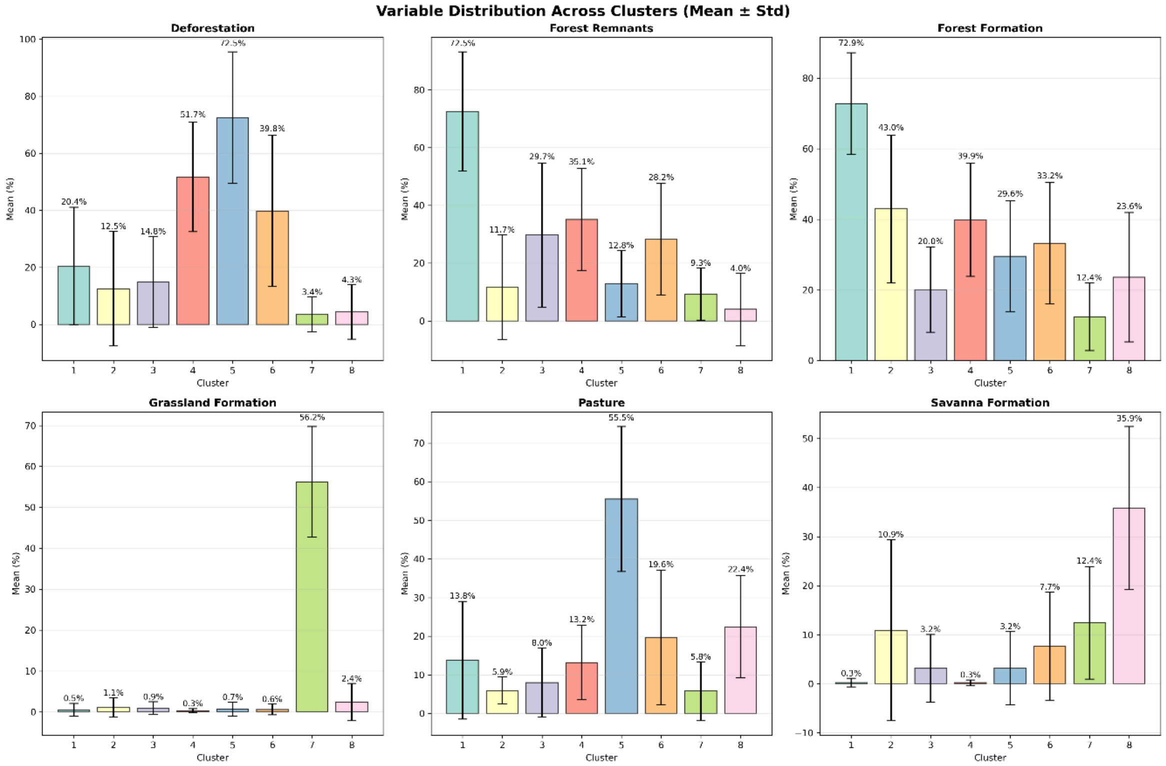


Figure 1. Cluster Characteristics

Cluster 6 encompasses 56 municipalities experiencing intensive agricultural development, particularly soybean cultivation (25.1%), combined with moderate deforestation pressure (39.8%). These areas maintain substantial forest formation (33.2%) and forest remnants (28.2%), indicating ongoing competition between agricultural expansion and forest conservation. The significant soybean presence reflects integration into global commodity markets and high economic pressure for continued forest conversion. REDD+ projects in this cluster face the challenge of competing with highly profitable agricultural activities while demonstrating that forest conservation can provide economically viable alternatives to further agricultural expansion.

Cluster 8 encompasses 181 municipalities in savanna-forest transition zones, characterized by 35.9% savanna formation and moderate agricultural activity (22.4% pasture, 6.1% soybean). These areas represent agricultural expansion zones where farming activities coexist with natural savanna ecosystems and remaining forest patches (23.6%). The relatively low historical deforestation (4.3%) and minimal recent deforestation pressure suggest these areas are experiencing gradual agricultural intensification rather than rapid forest conversion.

Cluster 3 represents specialized aquatic ecosystems, comprising 54 municipalities with extensive wetland coverage (29.7%) and floodable forests (20.8%). These areas maintain significant forest remnants (29.7%) and moderate deforestation pressure (14.8%), indicating relatively stable but vulnerable ecosystems. The high proportion of seasonally flooded areas provides critical habitat for biodiversity and supports traditional extractive economies based on fish, açaí, and other floodplain resources. REDD+ projects in this cluster can leverage the natural protection provided by flooding cycles while supporting community-based management of aquatic resources and preventing upland forest conversion.

The remaining clusters represent smaller, specialized ecosystem types. Cluster 4 (4.6% of municipalities) is distinguished by significant mangrove coverage (21.3%) in coastal areas with moderate deforestation pressure, representing critical marine-terrestrial interfaces. Cluster 7 (1.5% of municipalities) is dominated by natural grassland formations (56.2%), likely representing highland or naturally open areas with minimal deforestation pressure. Cluster 2 (1.1% of municipalities) features unique herbaceous sandbank vegetation (22.6%), representing specialized riverine or coastal environments. These smaller clusters highlight the ecological heterogeneity of the Amazon and the need for conservation strategies tailored to specific ecosystem types and their associated threats.

The majority of REDD+ projects are concentrated in forest conservation areas (Cluster 1) and intensive livestock conversion frontiers (Cluster 5), representing two fundamentally different conservation contexts. Projects located in Cluster 1 operate in well-preserved forest areas with minimal anthropic pressure, where REDD+ initiatives can focus on preventive conservation and supporting existing sustainable forest-based economies. Conversely, projects in Cluster 5 are positioned in areas experiencing the most severe deforestation pressure, where 72.5% historical deforestation and 55.5% pasture coverage create challenging conditions for forest conservation. This bimodal distribution suggests that REDD+ encompasses both low-risk preventive strategies in stable forest areas and high-risk reactive interventions in active deforestation hotspots.

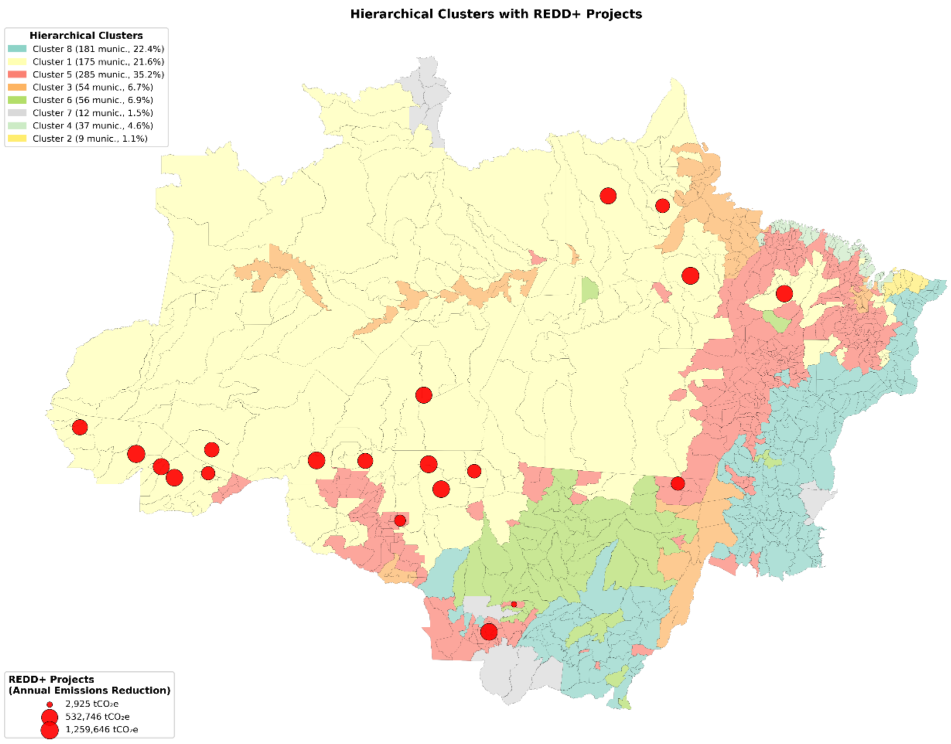


Figure 2. Map With Hierarchical Clusters and REDD+ Projects

The presence of REDD+ projects in wetland zones (Cluster 3) and soybean intensification corridors (Cluster 6) highlights the diversity of conservation challenges addressed by these initiatives. Projects in wetland systems can leverage natural flood protection while supporting traditional extractive economies, representing relatively low-risk conservation opportunities with multiple co-benefits. However, projects positioned in soybean corridors face direct competition with highly profitable agricultural activities, requiring demonstration of economically viable alternatives to forest conversion.

Table 1 shows the results of the regressions, which comprise the effects of predictors on probabilities of a municipality holding a REDD+ project, as well as the effects of predictors on annual emission reductions per project. Standard maximum likelihood logistic regression identified recent deforestation percentage as the sole significant predictor of REDD+ project placement. However, given the rare event nature of the data, these results should be interpreted with caution due to potential finite-sample bias. Firth penalized likelihood regression, recommended for rare events, confirmed recent deforestation percentage as the primary significant predictor.

Results indicate that a one standard deviation increase in recent deforestation percentage increases the odds of REDD+ project presence by approximately 54%.

Table 1. Regression Results

Variable	(1)	(2)	(3)
Longitude	0.1546 (0.6644)	0.0518 (0.8817)	-0.1670 (0.1303)
Latitude	-0.8313 (0.1060)	-0.5623 (0.2083)	-0.0811 (0.4746)
Total Deforestation (%)	-0.1143 (0.9559)	-0.6407 (0.7709)	-0.1218 (0.4206)
Recent Deforestation (%)	0.4793 *** (0.0036)	0.4314 *** (0.0047)	0.3732 *** (0.0000)
Forest Remnants (%)	2.551 * (0.0718)	2.032 * (0.0932)	0.1472 (0.4336)
Forest Formation (%)	1.5287 (0.2315)	1.4196 (0.1872)	0.3268 ** (0.0305)
Savanna Formation (%)	0.803 (0.6292)	1.2008 (0.4478)	0.1449 (0.3279)
Pasture (%)	2.6491 (0.1612)	2.6565 (0.1389)	0.2290 (0.1423)
Soybean (%)	0.2234 (0.8520)	0.7448 (0.5596)	-0.0352 (0.6995)
Wetland (%)	1.0872 (0.2872)	1.1898 (0.1089)	0.1114 (0.2324)
Pseudo R^2	0.3719		
Penalized Log-likelihood		-75.63	
Converged Iterations		55	
R^2			0.1095

Model (1) is the standard logistic model, which estimates the association between predictors and the probability that a municipality hosts at least one REDD+ project. The table reports log-odds coefficients, where the odds ratio equals exp(coefficient) and is therefore interpretable as the multiplicative change in the odds of *REDD Project Present* for a one-standard-deviation increase in the predictor, holding the others constant. McFadden's pseudo-R^2, reported as 0.3719, summarizes relative improvement over the null model (typical values are much lower than OLS R^2 and should be read comparatively, not absolutely). Model (2) is the Firth bias-reduced logistic regression, estimated to mitigate small-sample bias and potential separation. The model converges in 55 iterations, and yields the reported penalized log-likelihood (−75.63) at convergence. As in the standard logit, odds ratios are calculated as exp(coefficient) and correspond to a one-standard-deviation shift. To gauge intensive margins where projects exist, an OLS model (Model (3)) regresses log(Annual Emission Reductions From REDD+ Projects + 1) on the same standardized predictors. Coefficients can be read as semi-elasticities with respect to standardized predictors (approximately the proportional change in emissions reductions given a one-SD increase in the covariate).

This finding suggests that REDD+ projects are strategically targeted toward municipalities experiencing active deforestation pressure, aligning with the mechanism's preventive conservation objectives. Other environmental variables, while showing some association in the expected directions (e.g., forest coverage showing positive coefficients), did not achieve statistical significance in the rare event context. Geographic coordinates showed minimal influence, suggesting that REDD+ placement is driven more by environmental conditions than purely spatial factors.

For emissions reduction magnitude, ordinary least squares regression on log-transformed emissions reduction revealed two significant predictors: recent deforestation percentage ($\beta = 0.3732$, $p < 0.001$) and forest coverage percentage ($\beta = 0.3268$, $p = 0.0305$). The results indicate that municipalities with higher recent deforestation and greater forest coverage achieve larger emissions reductions. This dual pattern suggests that effective REDD+ projects require both urgency (deforestation pressure) and opportunity (remaining forest to protect).

Yet several transition-zone municipalities exhibit high recent deforestation without projects. Three mechanisms can depress siting probability there. First is enforcement capacity, as lower municipal/state enforcement raises baseline uncertainty and verification costs. Second is related to tenure constraints, when overlapping claims (unclear or disputed titles, lack of demarcation for Indigenous territories, informal settlements, or cadastre gaps) and weak land administration increase legal risks. Third is commodity exposure, as high soy/cattle intensity elevates leakage and permanence risks, discouraging developers despite apparent additionality. These mechanisms are consistent with our clusters: frontier-adjacent groups combine higher pasture/soy shares and lower protected-area coverage, aligning with greater contracting frictions and verifier risk.

Taken together, the maps and models indicate a risk-aligned siting pattern. Projects are concentrated along the southern arc of deforestation and in municipalities with elevated recent clearing, consistent with H1 (targeting risk). By contrast, a simple "more forest, more projects" relationship is weak once recent clearing is controlled for, suggesting that pressure rather than stock is the dominant correlate of siting in our data. The southward tilt likely reflects the spatial distribution of threats as well as program frictions—accessibility, institutional capacity, and monitoring logistics.

4. Discussion

The evidence speaks clearly to the two hypotheses set out in the introduction. H1 (targeting risk) is strongly supported: recent deforestation is the only robust, statistically significant correlate of REDD+ siting across both MLE and Firth logistic models. By contrast, H2 (remaining stock → siting) receives limited support once recent clearing is controlled for. We therefore characterize siting as primarily risk-aligned rather than simply stock-seeking. Any positive association between recent clearing, forest cover, and reported emission reductions is presented as descriptive context only; because these volumes are reported at the project level and endogenous to siting and project design, we do not draw intensive-margin inferences.

This pattern is consistent with the broader land-use literature on the Amazon. Meta-analyses and comparative reviews emphasize the central role of cattle-dominated frontiers, market access, and governance cycles in shaping deforestation risk (Busch & Ferretti-Gallon, 2017; Hänggli et al., 2023). Recent work on Southwest Pará also documents how political shifts translate into spatially concentrated clearing along accessible margins (Jakimow et al., 2023). Our cluster diagnostics mirror this history, revealing a “bimodal” allocation: projects appear both in well-preserved cores (preventive conservation) and along livestock/agriculture conversion belts (reactive “line-of-defense”). That bimodality resonates with earlier accounts of policy slack and resurgence in clearing (Prates & Bacha, 2011; Young, 1998) and with evidence that federal enforcement intensity shapes spatial outcomes (Correia-Silva & Rodrigues, 2019). In short, siting seems to follow where risk accumulates rather than how much forest remains—an allocation logic that aligns with additionality concerns.

Our results also inform, but do not resolve, the debate on project integrity. Findings of over-crediting tied to inflated baselines in voluntary projects (West et al., 2020) stand in tension with evaluations reporting positive average effects (Griscom et al., 2022). Risk-targeted siting increases the plausibility that projects address genuine counterfactual threats; however, baseline construction and leakage remain open questions. The descriptive co-movement between recent clearing, forest cover, and reported reductions is compatible with real avoided emissions or with baselines that track pressure. A cautious policy takeaway - outside the scope of this paper’s causal claims - is to pair any risk-aware siting with independent baseline audits and systematic leakage accounting, especially along savanna-forest transitions and soy corridors where displacement risks are salient (Oliveira Junior et al., 2024). Jurisdictional instruments and fund governance (e.g., Amazon Fund assessments and Earth Innovation Institute guidance) offer practical avenues to align project-level incentives with basin-scale goals.

Practically, the pressure-stock lens could be scaled programmatically (national/jurisdictional targeting grids) and then gated by minimum institutional thresholds, like enforceability (monitoring and sanction capacity), tenure security (clear, uncontested rights), and social safeguards (meaningful community participation). This reframes siting from a purely technical allocation into a governance problem: high-pressure areas are targetable, but only those passing the institutional gate are truly implementable and durable for crediting. Where thresholds are not met, deployment should shift to jurisdictional or co-governed arrangements that can address tenure regularization and enforcement gaps before project crediting. Comparative evidence from sub-Saharan Africa's green-infrastructure planning (Asibey et al., 2024), where outcomes under land-use pressure depend on co-governance and customary tenure, supports this framing: institutional context mediates conservation returns.

The limited support for H2 likely reflects binding implementation frictions - transaction costs, tenure/security constraints, and verifier access - that steer projects toward edges where threat (and thus expected additionality) is noticeable, rather than toward large, intact stocks per se. Under a pressure-stock trade-off, this is consistent with threat-mitigation theory when budgets and institutional capacity are scarce.

Limitations suggest concrete extensions. Name-based matching and municipal aggregation can mask within-boundary heterogeneity and multi-jurisdiction footprints; improved entity resolution and project-footprint rasters would sharpen identification. Residual spatial dependence may bias uncertainty; spatial logit/probit or eigenvector-filtered Firth models are natural next steps. Heterogeneity across project designs likely interacts with pressure and stock, motivating hierarchical or random-coefficient approaches. Finally, causal evaluation of emission outcomes calls for quasi-experimental designs (e.g., synthetic control and staggered event studies; see Sills et al., 2022) layered on the descriptive siting evidence reported here. Together, these steps would move the discussion from where projects locate toward how credible and how durable their claimed impacts are—without retreating from the core insight that risk-aware siting is a necessary condition for additionality at scale.

These results inform, but do not settle, ongoing debates about additionality and integrity. Risk-aligned placement increases the plausibility that projects address genuine counterfactual threats; however, siting patterns alone cannot adjudicate baseline inflation or leakage. Any co-movement between pressure, forest cover, and project-reported emission reductions should be read as descriptive, not causal, given the endogeneity of those outcomes to siting and design choices. Methodologically, the study offers a transparent template that combines rare-events inference with spatial autocorrelation diagnostics (Moran's I, LISA) and PCA-assisted clustering to interpret heterogeneous land-use contexts. Theoretically, the results sharpen pressure-stock targeting under spatial dependence and provide testable benchmarks for future causal evaluations

Finally, while this paper does not prescribe an allocation rule, its findings can be interpreted through a simple pressure-stock lens that is compatible with routine monitoring. Any practical use of that lens should be paired with independent baseline audits, leakage accounting along cattle and soy corridors, and jurisdictional coordination so project-level incentives aggregate to basin-scale integrity. Moving from where projects are sited toward how credible and how durable their claimed impacts are will determine whether REDD+ can deliver climate-relevant, socially robust forest protection at scale.

Authors contributions

Mr. Thiago D. Gil and Dr. Wesley Mendes-Da-Silva were responsible for study design and revising. Mr. Thiago D. Gil was responsible for data collection and drafted the manuscript and Dr. Wesley Mendes-Da-Silva revised it. All authors read and approved the final manuscript.

Funding

This work was supported by The National Council for Scientific and Technological Development of Brazil (CNPq) [project number 309682/2022-3] and by The Sao Paulo School of Business Administration (FGV EAESP).

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Macrothink Institute.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

References

Aguiar, P. F. D. (2022). Deforestation of the paraense amazon forest. International Journal of Environmental Resilience *Research and Science, 4*(1), 01-11. https://doi.org/10.48075/ijerrs.v3i4.25590

Asibey, M. O., Baah-Ennumh, T. Y., & Amponsah, O. (2024). Revisiting the garden city concept and urban green infrastructure discourse in sustainable city planning in sub-Saharan Africa. *Local Environment, 29*(12), 1538-1552. https://doi.org/10.1080/13549839.2024.2386966

Barrozo, V. P., De Sousa, H. A., Santos, M. A. O., De Almeida, L. C. P., & Weiss, C. (2019). Desperdício de alimentos: O peso das perdas para os recursos naturais. *Revista Agroecossistemas, 11*(1), 75. https://doi.org/10.18542/ragros.v11i1.6551

Benevides, M., & Almeida, L. (2015). Desmatamento no Brasil. *Sustainability in Debate, 6*(3), 182-213. https://doi.org/10.18472/SustDeb.v6n3.2015.17232

Bonat, W. H., Paiva, M. F., & Sliwiany, R. M. (2010). Análise espacial intra-urbana da qualidade de vida em Curitiba. *Revista Brasileira de Qualidade de Vida, 1*(2). https://doi.org/10.3895/S2175-08582009000200004

Börner, J., Baylis, K., Corbera, E., Ezzine-de-Blas, D., Honey-Rosés, J., Persson, U. M., & Wunder, S. (2010). Direct conservation payments in the Brazilian Amazon: Scope and equity implications. *Ecological Economics, 69*(6), 1272-1282. https://doi.org/10.1016/j.ecolecon.2009.11.003

Börner, J., Baylis, K., Corbera, E., Ezzine-de-Blas, D., Honey-Rosés, J., Persson, U. M., & Wunder, S. (2019). Amazon Fund 10 years later: Lessons from the world's largest REDD+ program. *Forests, 10*(3), 272. https://doi.org/10.3390/f10030272

Busch, J., & Ferretti-Gallon, K. (2017). What drives deforestation and what stops it? A meta-analysis. *Review of Environmental Economics and Policy, 11*(1), 3-23. https://doi.org/10.1093/reep/rew013

Butt, E. W., Rap, A., Baldock, J., Spracklen, C. S., Vischetti, M., Western, L. M., ... Spracklen, D. V. (2023). Amazon deforestation causes strong regional warming. *Proceedings of the National Academy of Sciences, 120*(45), e2309123120. https://doi.org/10.1073/pnas.2309123120

Câmara, G., Carvalho, M. S., Cruz, O. G., & Correa, V. (2002). Análise espacial de áreas. In G. A. M. V. Fuks, S. D., Carvalho, M. S., & Câmara (Eds.), *Análise espacial de dados geográficos. Divisão de Processamento de Imagens* - Instituto Nacional de Pesquisas Espaciais.

Coelho, A. D. S., & De Toledo, P. M. (2024). Public policies and the dynamics of forest conversion in the anthropocene of the Amazon paraense. *Revista Delos, 17*(52), e1260. https://doi.org/10.55905/rdelosv17.n52-006

Conceição, K. V. D., Chaves, M. E. D., & Mataveli, G. A. V. (2020). Land use and land cover mapping in a priority municipality for deforestation control actions in the Amazon using GEOBIA. *Revista Brasileira de Cartografia, 72*(4), 574-587. https://doi.org/10.14393/rbcv72n4-53192

Correia-Silva, D. C., & Rodrigues, M. (2019). Federal enforcement and reduction of deforestation in the Brazilian Amazon. *Estação Científica (UNIFAP), 9*(1), 75. https://doi.org/10.18468/estcien.2019v9n1.p75-88

CPT (Org.). (2017). Comissão Pastoral da Terra. *Atlas de Conflitos na Amazônia*. Entremares.

Creswell, J. W. (2010). *Projeto de Pesquisa: Métodos Qualitativos, Quantitativos e Mistos*. Artmed.

Cromberg, M., Duchelle, A. E., & Rocha, I. de O. (2014). Local participation in REDD+: Lessons from the eastern Brazilian Amazon. *Forests, 5*(4), 579-598. https://doi.org/10.3390/f5040579

Dittmar, H., & Mrozinski, D. R. (2022). Utilização dos relatórios automatizados de alertas de desmatamento na melhoria do processo investigativo criminal ambiental. *Revista Brasileira de Ciências Policiais, 13*(9), 105-130. https://doi.org/10.31412/rbcp.v13i9.952

Duchelle, A. E., Cromberg, M., Gebara, M. F., Guerra, R., Melo, T., Larson, A., ... Sunderlin, W. D. (2014). Linking forest tenure reform, environmental compliance, and incentives: Lessons from REDD+ initiatives in the Brazilian Amazon. *World Development, 55*, 53-67. https://doi.org/10.1016/j.worlddev.2013.01.014

Earth Innovation Institute. (2023). The new carbon market and the Brazilian Amazon forest: Opportunities and challenges for jurisdictional REDD+. Earth Innovation Institute. [Online] Available: https://earthinnovation.org/uploads/2023/05/EII-New-Carbon-Market-Brazilian-Amazon-Forest.pdf

Ellwanger, J. H., Kulmann-Leal, B., Kaminski, V. L., Valverde-Villegas, J. M., da Veiga, A. B. G., Spilki, F. R., ... Chies, J. A. B. (2020). Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *Anais da Academia Brasileira de Ciências, 92*(1), e20191375. https://doi.org/10.1590/0001-3765202020191375

Esteves, P. M. da S. V., & Cruz, F. S. (2022). Avaliação dos impactos do processo de desertificação no Seridó Ocidental a partir de indicadores biofísicos e sociais. *Research, Society and Development, 11*(3), e1411326082. https://doi.org/10.33448/rsd-v11i3.26082

FAPESPA. (2021). Fundação Amazônia Paraense de Amparo à Pesquisa. *Anuário Estatístico*. [Online] Available: http://www.fapespa.pa.gov.br/menu/148

FIRJAN. (2018). Federação da Indústria do Rio de Janeiro. *Índice FIRJAN de Desenvolvimento Municipal*. [Online] Available: https://www.firjan.com.br/ifdm/downloads

Firth, D. (1993). Bias reduction of maximum likelihood estimates. *Biometrika, 80*(1), 27-38. https://doi.org/10.1093/biomet/80.1.27

Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., ... Hirota, M. (2024). Critical transitions in the Amazon forest system. *Nature*, 626(7999), 555-564. https://doi.org/10.1038/s41586-023-06970-0

Freitas, M. A. B., Magalhães, J. L. L., Carmona, C. P., Arroyo-Rodríguez, V., Vieira, I. C. G., & Tabarelli, M. (2021). Intensification of açaí palm management largely impoverishes tree assemblages in the Amazon estuarine forest. *Biological Conservation, 261*, 109251. https://doi.org/10.1016/j.biocon.2021.109251

Gebara, M. F. (2014). *REDD+ policy networks in Brazil: Constraints and opportunities for successful policy making* [Doctoral dissertation, London School of Economics and Political Science]. LSE Research Online. https://doi.org/10.5751/ES-06744-190353

Giatti, O. F., Mariosa, P. H., Alfaia, S. S., Silva, S. C. P. da, & Pereira, H. dos S. (2021). Potencial socioeconômico de produtos florestais não madeireiros na reserva de desenvolvimento sustentável do Uatumã, Amazonas. *Revista de Economia e Sociologia Rural, 59*(3). https://doi.org/10.1590/1806-9479.2021.229510

Griscom, B. W., Ellis, P. W., Burivalova, Z., Halperin, J., Marthinus, D., Runting, R. K., ... Ellis, E. A. (2022). A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conservation Biology, 37*(2), e14000. https://doi.org/10.1111/cobi.14000

Guízar-Coutiño, A., Jones, J. P. G., Balmford, A., Carmenta, R., & Coomes, D. A. (2022). A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conservation Biology, 36*(6), e13970. https://doi.org/10.1111/cobi.13970

Hänggli, A., Levy, S. A., Armenteras, D., Bovolo, C. I., Brandão, J., Rueda, X., & Garrett, R. D. (2023). A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome. *Environmental Research Letters, 18*(7), 073001. https://doi.org/10.1088/1748-9326/acd408

Herrera, J. A., & Moreira, R. P. (2013). Resistência e conflitos sociais na amazônia: A luta contra o empreendimento Hidrelétrico de Belo Monte. *Revista Campo-Território, 8*(16), 130-151. https://doi.org/10.14393/RCT81619861

IBGE. (2021a). Instituto Brasileiro de Geografia e Estatística. Downloads. [Online] Available: https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html

IBGE. (2021b). Instituto Brasileiro de Geografia e Estatística. *Sistema IBGE de Recuperação Automática-SIDRA*. [Online] Available: http://www.sidra.ibge.gov.br/bda/cempre/default.asp?z=t&o=12&i=P

Jakimow, B., Baumann, M., Salomão, C., Bendini, H., & Hostert, P. (2023). Deforestation and agricultural fires in South-West Pará, Brazil, under political changes from 2014 to 2020. *Journal of Land Use Science, 18*(1), 176-195. https://doi.org/10.1080/1747423X.2023.2195420

Lapola, D. M., Pinho, P., Barlow, J., Aragão, L. E., Berenguer, E., Carmenta, R., ... Silvestrini, R. A. (2023). The drivers and impacts of Amazon forest degradation. *Science, 379*(6630), eabp8622. https://doi.org/10.1126/science.abp8622

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Proceedings of the National Academy of Sciences, 118*(47), e2023252118. https://doi.org/10.1038/s41467-021-22840-7

Lopes, C. L., Chiavari, J., & Segovia, M. E. (2023). *Brazilian Environmental Policies and the New European Union Regulation for Deforestation-Free Products: Opportunities and Challenges*. Climate Policy Initiative.

Marschner, W. (2014). O Vínculo Com Agricultura Familiar Como Critério De Sustentabilidade: Um Estudo De Caso No Paraná. *Cadernos de Agroecologia, 9*(4), 1-15. https://revista.aba-agroecologia.org.br/cad/article/view/16415

May, P. H., Millikan, B., & Gebara, M. F. (2011). *The context of REDD+ in Brazil: Drivers, agents and institutions*. CIFOR. https://doi.org/10.17528/cifor/003287

Miyamoto, M. (2020). Poverty reduction saves forests sustainably: Lessons for deforestation policies. *World Development, 127*, 104746. https://doi.org/10.1016/j.worlddev.2019.104746

Neves, J. T., & Bizawu, K. (2019). O extrativismo da madeira na Amazônia e seus impactos ambientais: a contribuição do protocolo de Kyoto para o desenvolvimento sustentável. *Argumentum Journal of Law, 20*(2), 465-483. http://ojs.unimar.br/index.php/revistaargumentum/article/view/1018

Nishimwe, O., Hakizimana, N., Nahayo, L., Maniragaba, A., & Nirere, T. (2021). Relationship between human activities and deforestation in Karongi District of Rwanda. *Journal of Forests, 8*(1), 1-12. https://doi.org/10.18488/journal.101.2021.81.1.12

Oliveira Junior, L., De Souza Filho, J. S., Ferreira, B. G., & Souza Junior, C. (2024). Secondary growth deforestation leakage in the Pará beef cattle purchasing zone. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-3-2024*, 371-376. https://doi.org/10.5194/isprs-archives-XLVIII-3-2024-371-2024

Prates, R. C., & Bacha, C. J. C. (2011). Os processos de desenvolvimento e desmatamento da Amazônia. *Economia e Sociedade, 20*(3), 601-636. https://doi.org/10.1590/S0104-06182011000300006

Rodrigues, R. J., Oliveira Santos, M. A., Soares, F. I. L., Paiva, F. C. S., & Oliveira, A. M. (2025). The Spatial Patterns of Deforestation in Pará, Brasil: From Economic Necessity to Environmental Threat. *Environmental Management and Sustainable Development, 14*(2), 20-43. https://doi.org/10.5296/emsd.v14i2.22928

Roopsind, A., Sohngen, B., & Brandt, J. (2019). Evidence that a national REDD+ program reduces tree cover loss and carbon emissions in a high forest cover, low deforestation country. *Proceedings of the National Academy of Sciences, 116*(49), 24492-24499. https://doi.org/10.1073/pnas.1904027116

Santos, M. A. O., Soares, F. I. L., Da Costa, M. B., Paes, D. C. A. de S., & Nascimento, M. A.

de A. (2023). Challenges and perspectives in the management of solid urban waste in municipalities in Pará State: A critical and multifaceted analysis. *Revista de Gestão Social e Ambiental, 18*(3), e04592. https://doi.org/10.24857/rgsa.v18n3-040

Sills, E. O., Herrera, D., Kirkpatrick, A. J., Brandão Jr, A., Dickson, R., Hall, S., ... West, T. A. (2022). Estimating the impacts of local policy innovation: The synthetic control method applied to tropical deforestation. *Plos One, 17*(3), e0265030. https://doi.org/10.1371/journal.pone.0265030

Silva, J. S. (2019). The opportunity cost of preserving the Brazilian Amazon forest. *Agricultural and Resource Economics Review, 48*(2), 197-218. https://doi.org/10.1111/agec.12478

Simonet, G., Subervie, J., Ezzine-de-Blas, D., Cromberg, M., & Duchelle, A. E. (2019). Effectiveness of a REDD+ project in reducing deforestation in the Brazilian Amazon. *American Journal of Agricultural Economics, 101*(1), 211-229. https://doi.org/10.1093/ajae/aay028

Sunderlin, W. D., Larson, A. M., Duchelle, A. E., Resosudarmo, I. A. P., Huynh, T. B., Awono, A., & Dokken, T. (2014). How are REDD+ proponents addressing tenure problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam. *World Development, 55*, 37-52. https://doi.org/10.1016/j.worlddev.2013.01.013

Van der Hoff, R., Rajão, R., & Leroy, P. (2015). Clashing interpretations of REDD+ "results" in the Amazon Fund. *Global Environmental Politics, 15*(4), 34-54. https://doi.org/10.1162/GLEP_a_00323

West, T. A., Börner, J., Sills, E. O., & Kontoleon, A. (2020). Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proceedings of the National Academy of Sciences, 117*(39), 24188-24194. https://doi.org/10.1073/pnas.2004334117

West, T. A., Bomfim, B., & Haya, B. K. (2024). Methodological issues with deforestation baselines compromise the integrity of carbon offsets from REDD+. *Global Environmental Change, 87*, 102863. https://doi.org/10.1016/j.gloenvcha.2024.102863

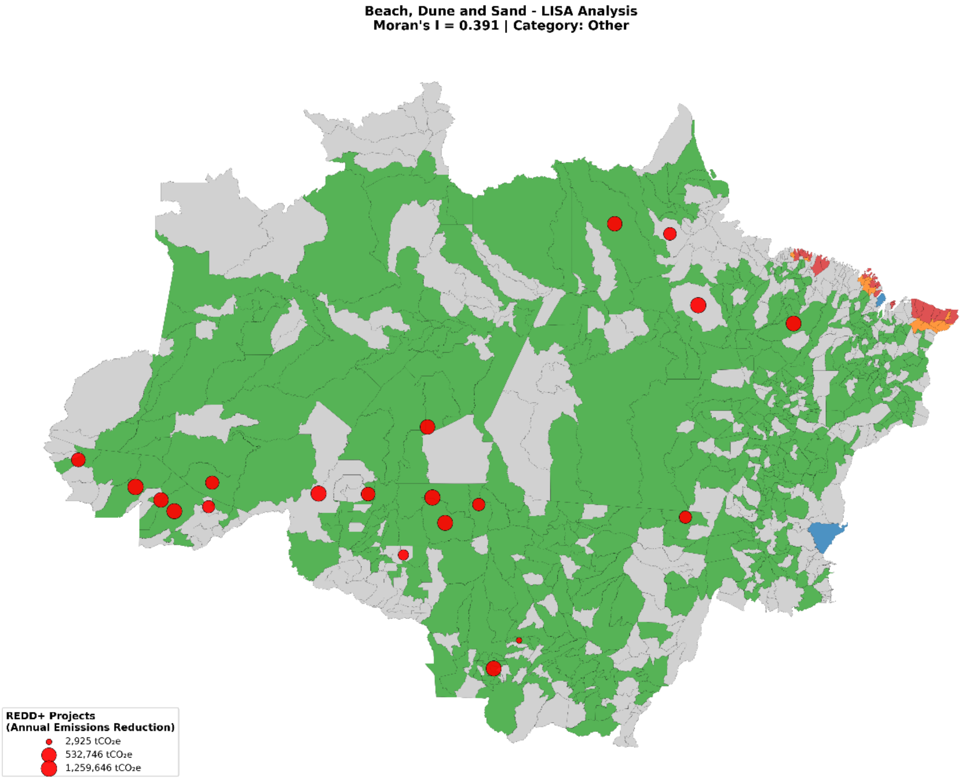
Young, C. E. F. (1998). Public policies and deforestation in the Brazilian Amazon. *Planejamento e Políticas Públicas, 0*(18). [Online] Available: http://www.ipea.gov.br/ppp/index.php/PPP/article/view/103

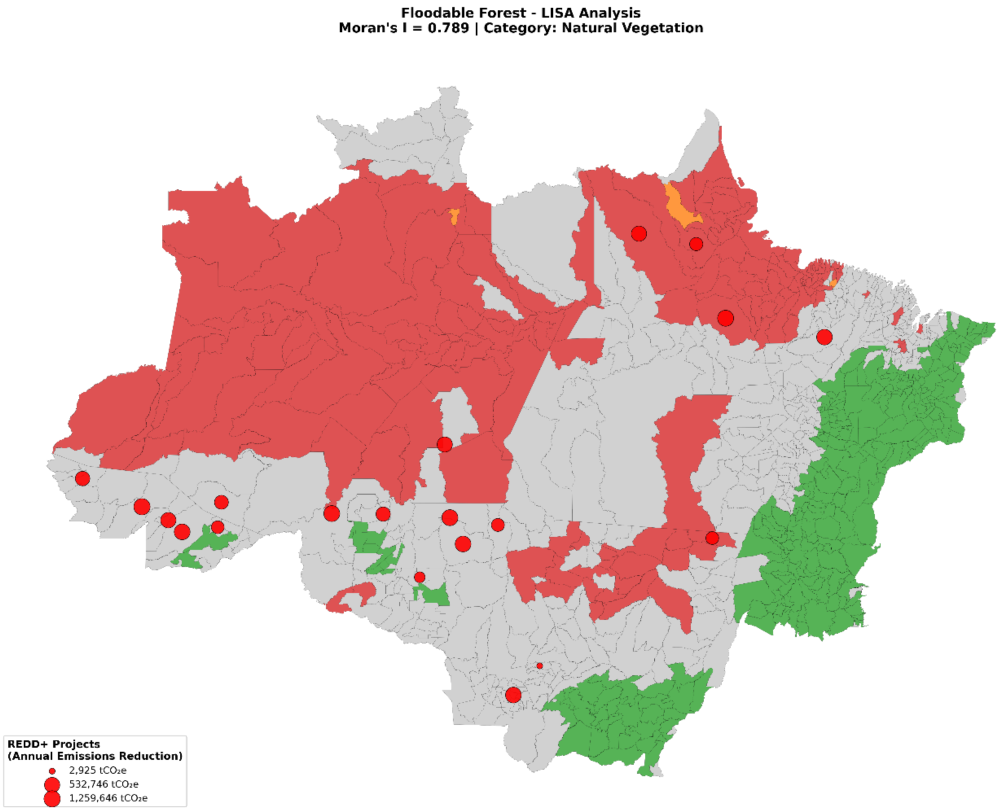
Environmental Management and Sustainable Development
ISSN 2164-7682
2025, Vol. 14, No. 2

Appendix

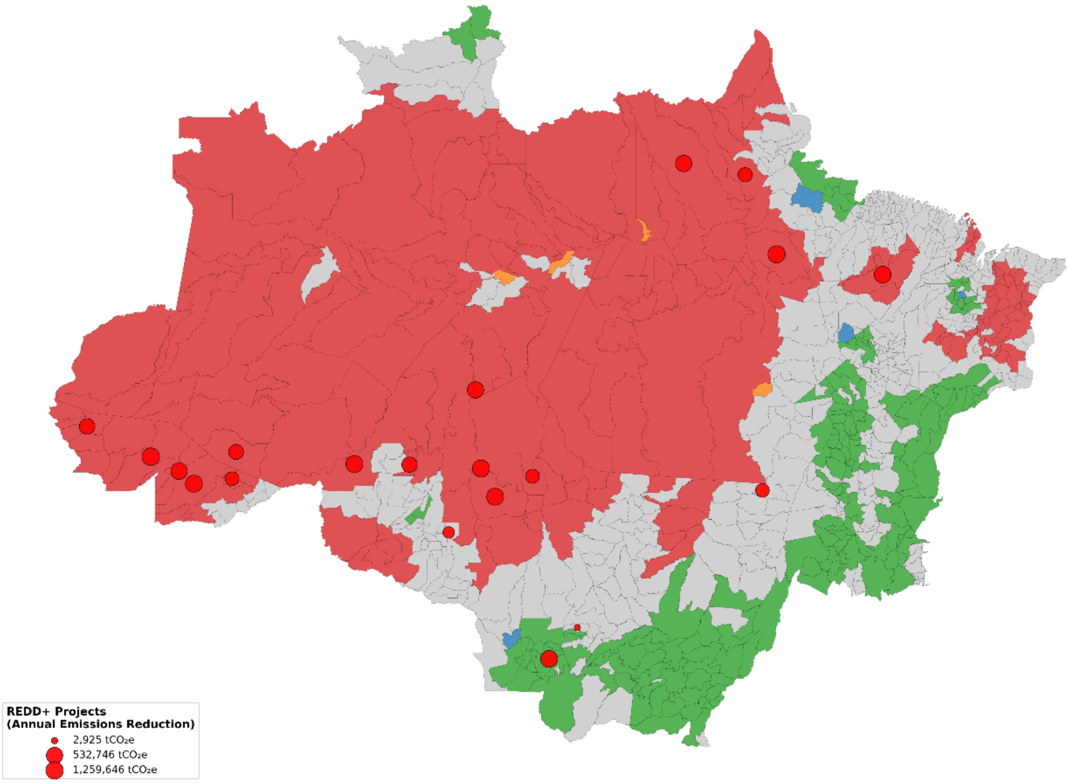
Appendix A

LISA Analysis and Maps

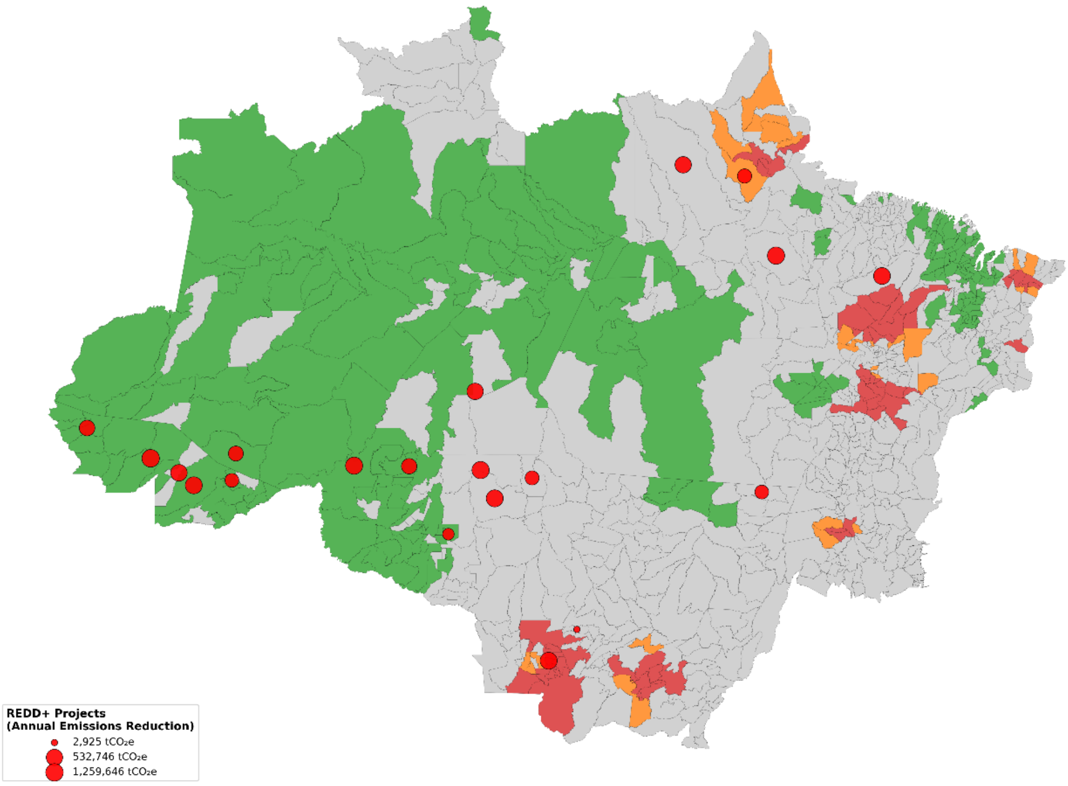


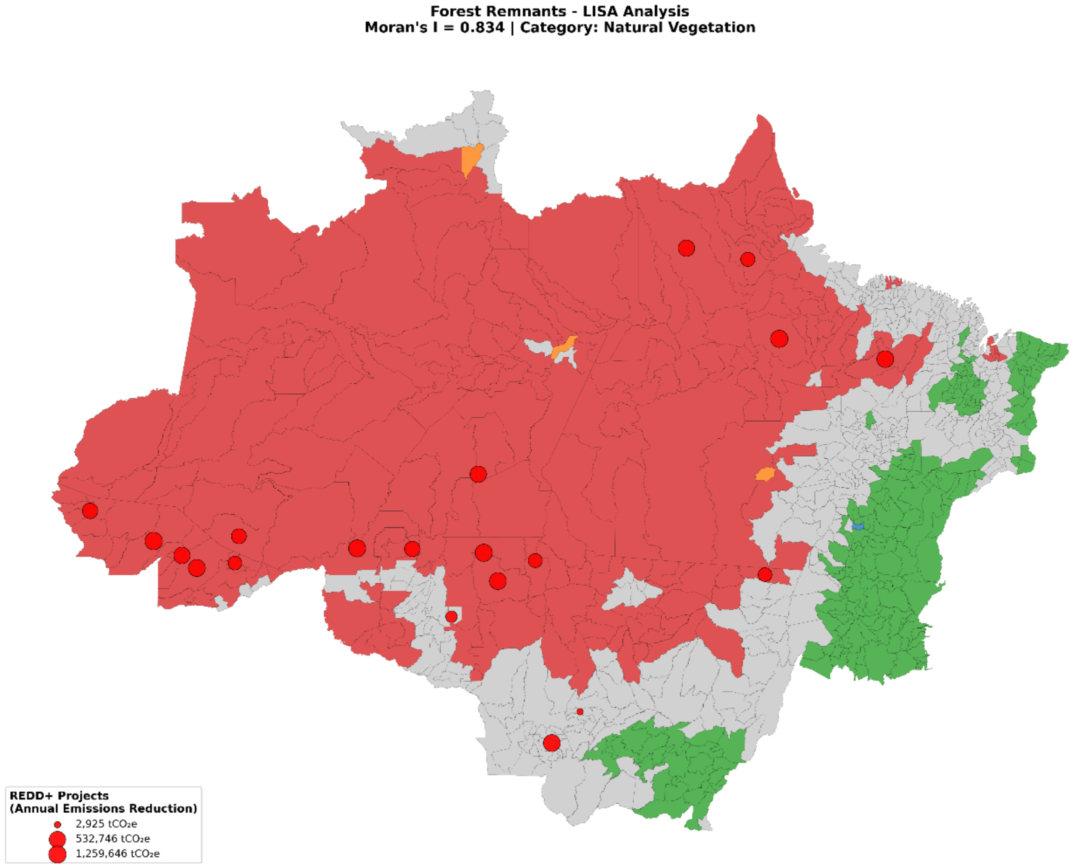


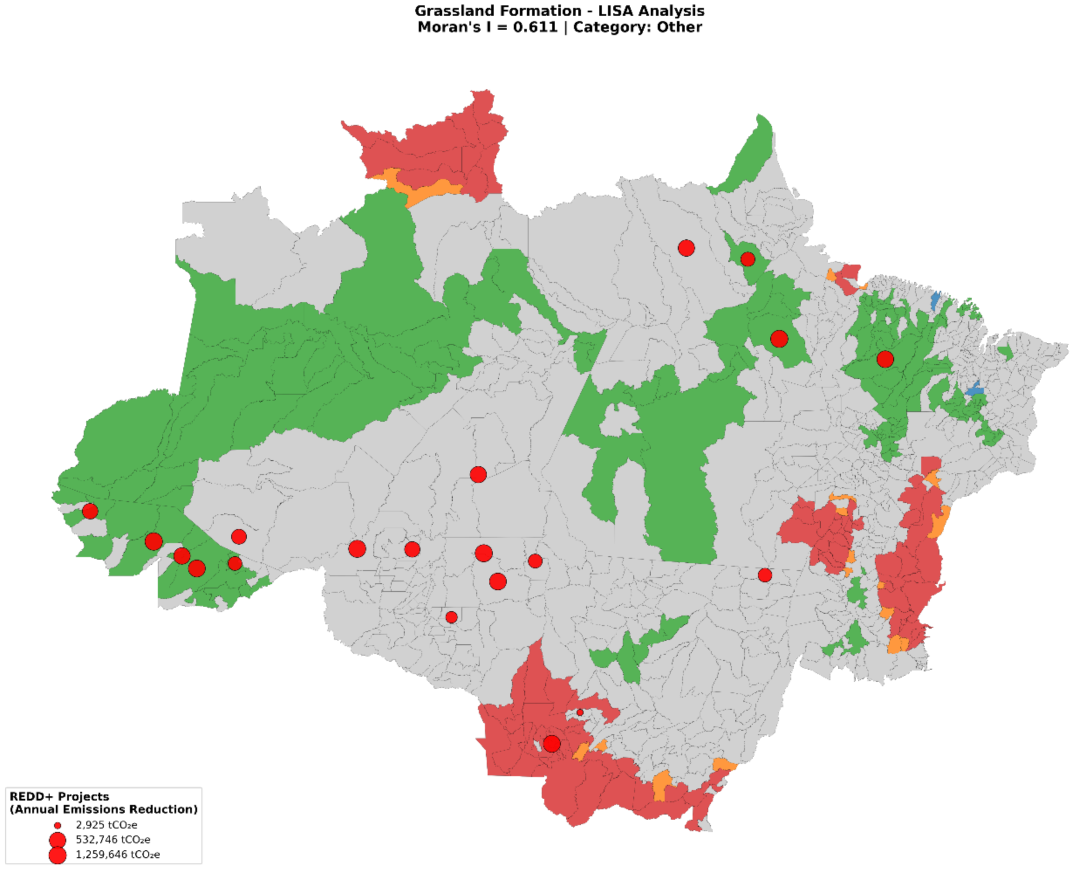
Forest Formation - LISA Analysis
Moran's I = 0.664 | Category: Natural Vegetation

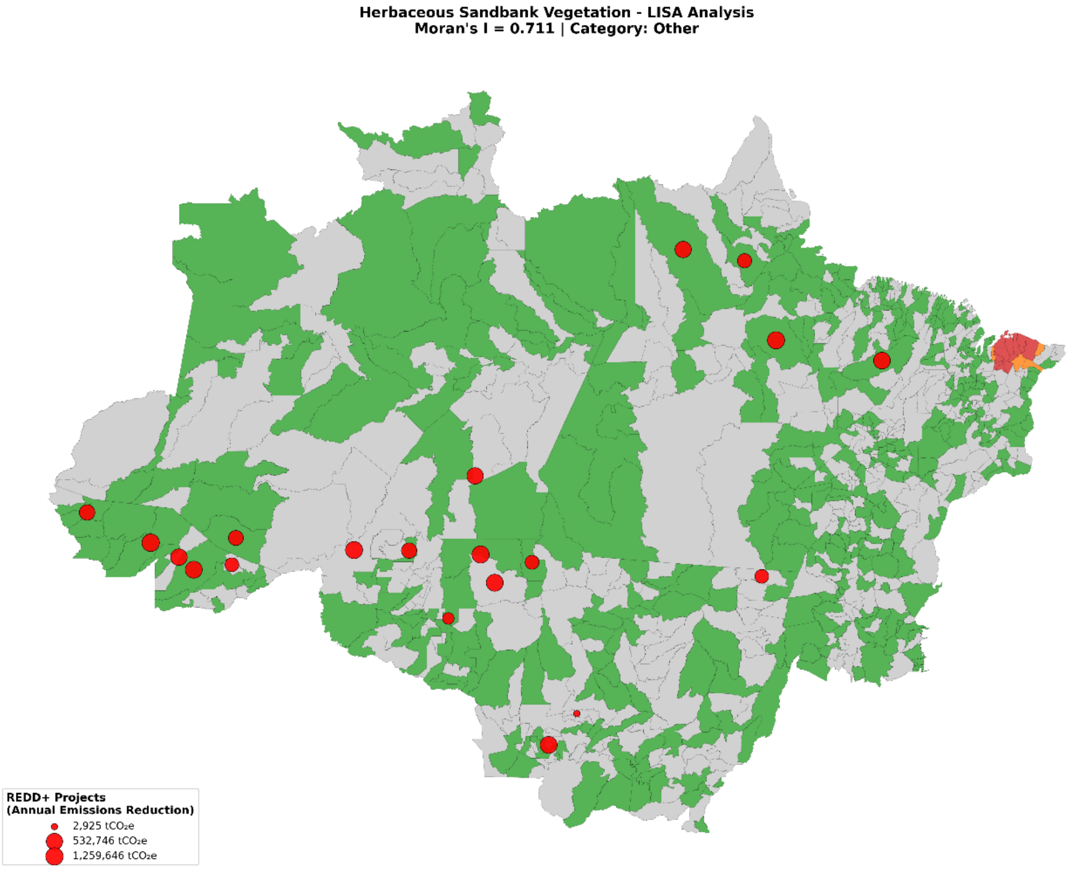


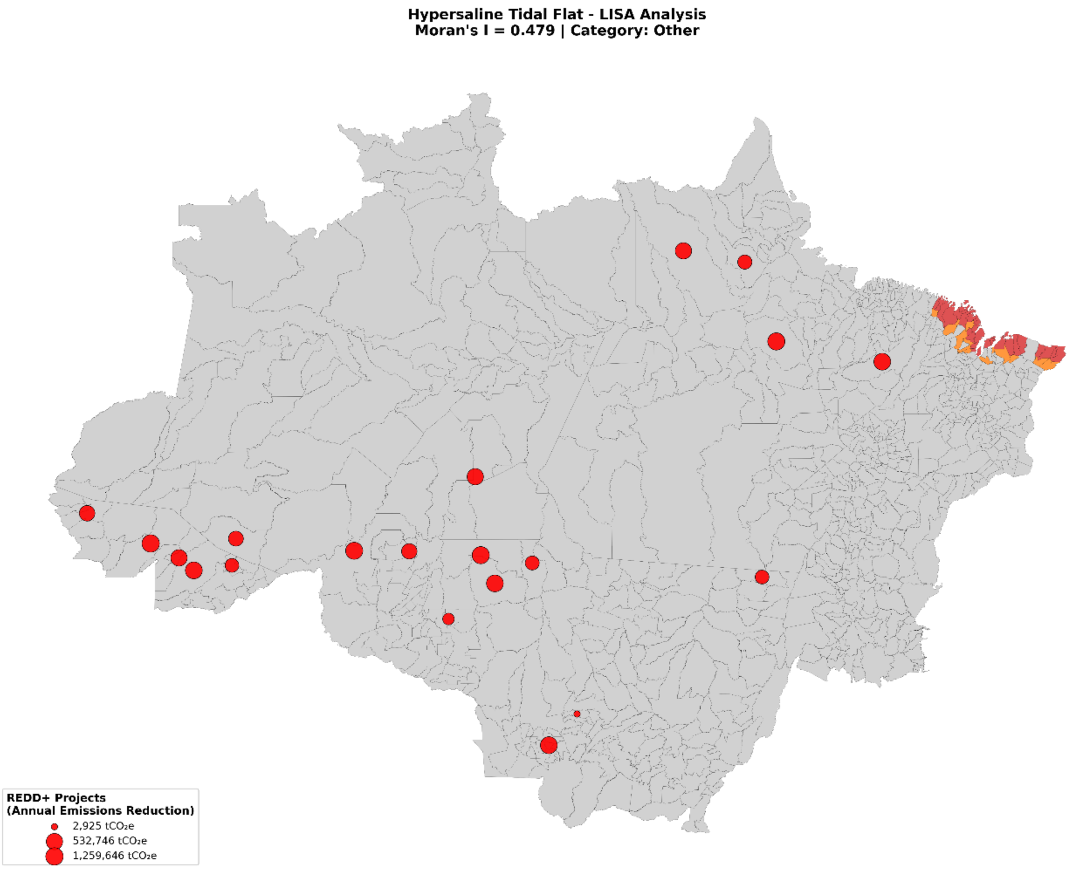
Forest Plantation - LISA Analysis
Moran's I = 0.366 | Category: Natural Vegetation

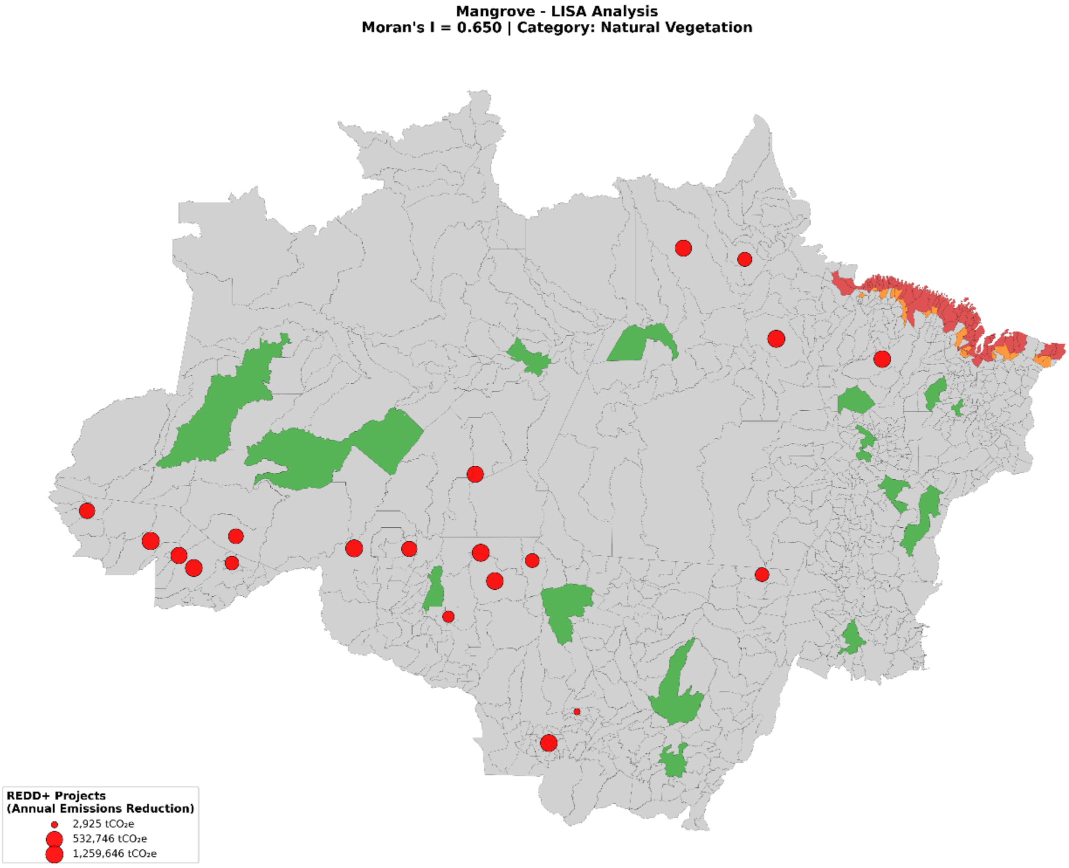


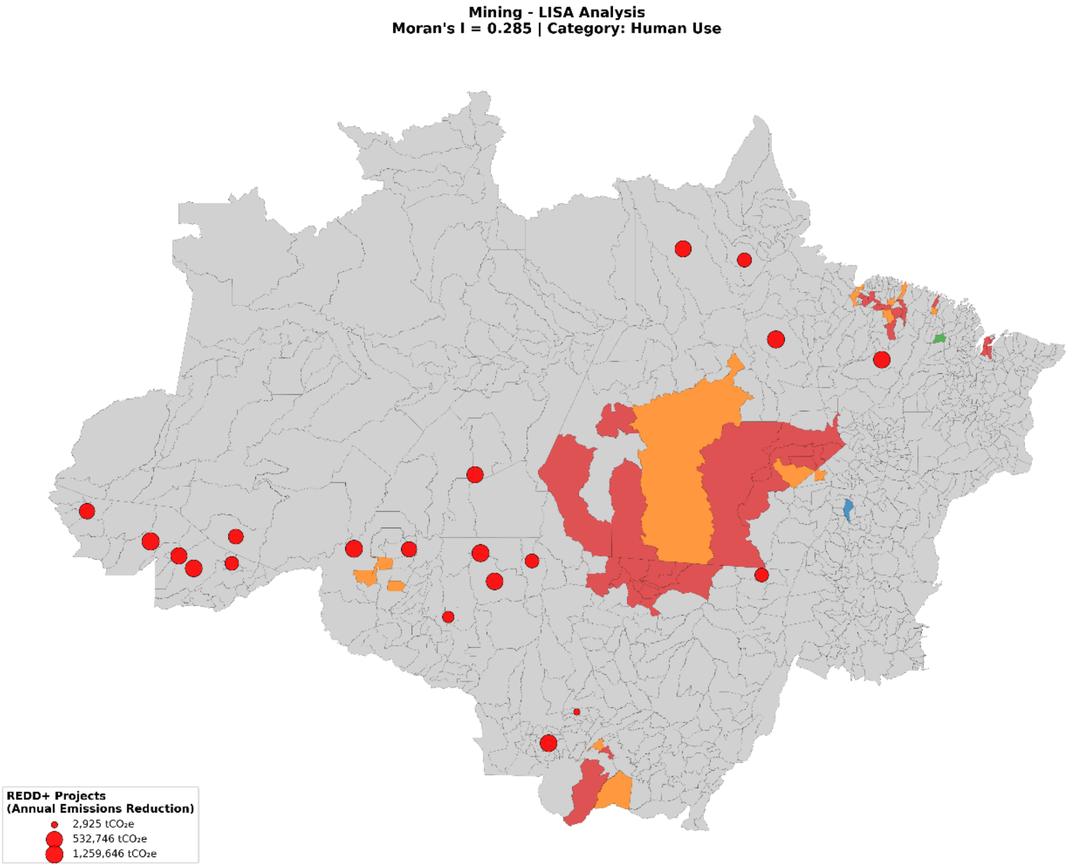

Forest Remnants - LISA Analysis
Moran's I = 0.834 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

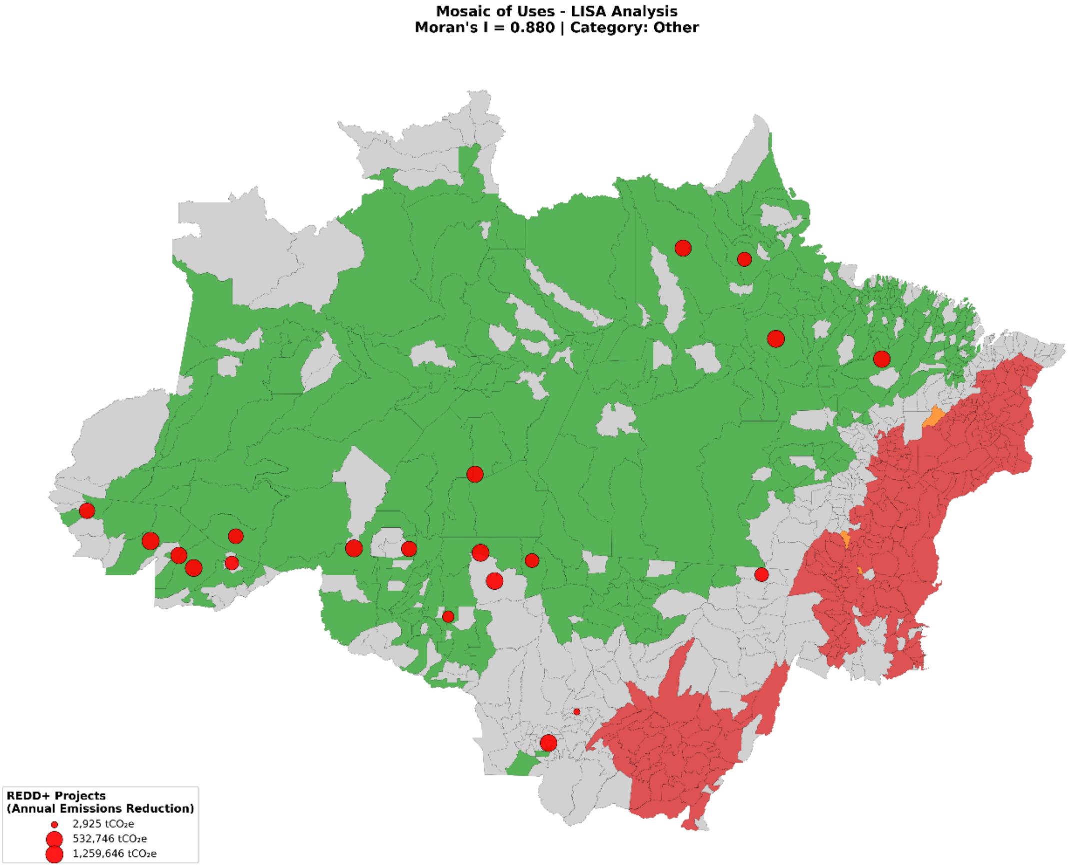

Grassland Formation - LISA Analysis
Moran's I = 0.611 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

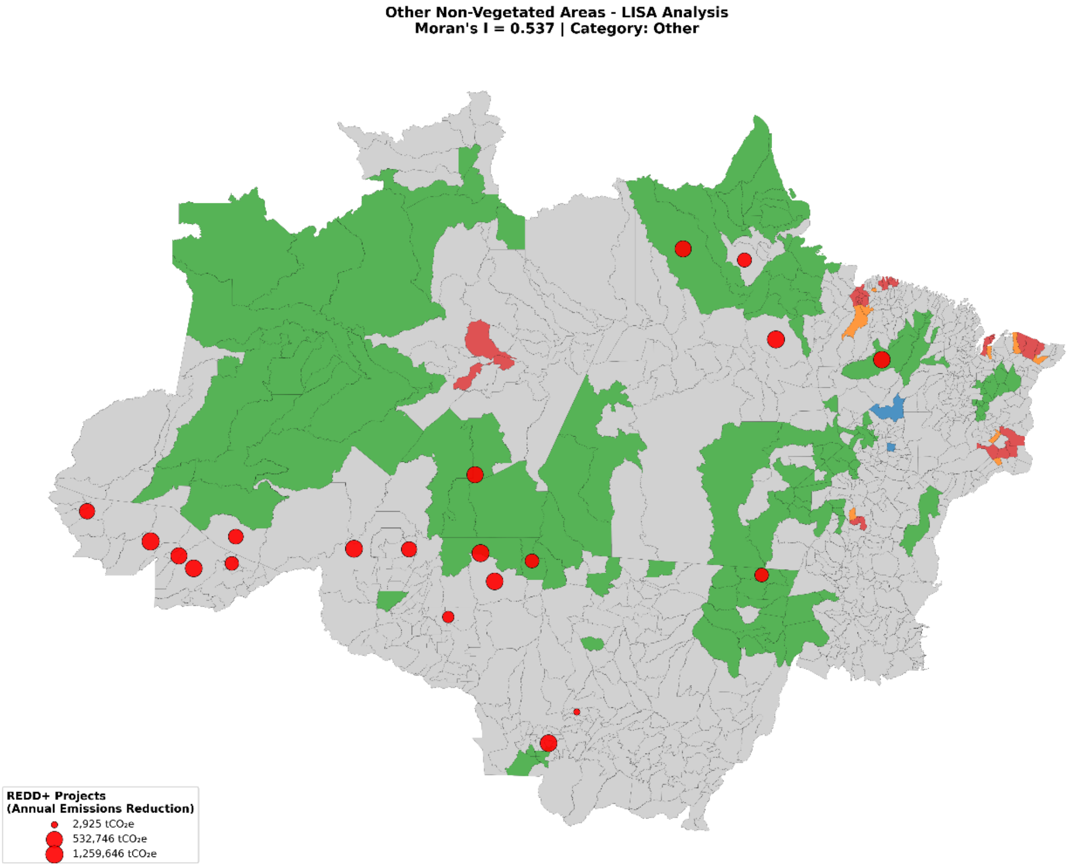

Herbaceous Sandbank Vegetation - LISA Analysis
Moran's I = 0.711 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Hypersaline Tidal Flat - LISA Analysis
Moran's I = 0.479 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

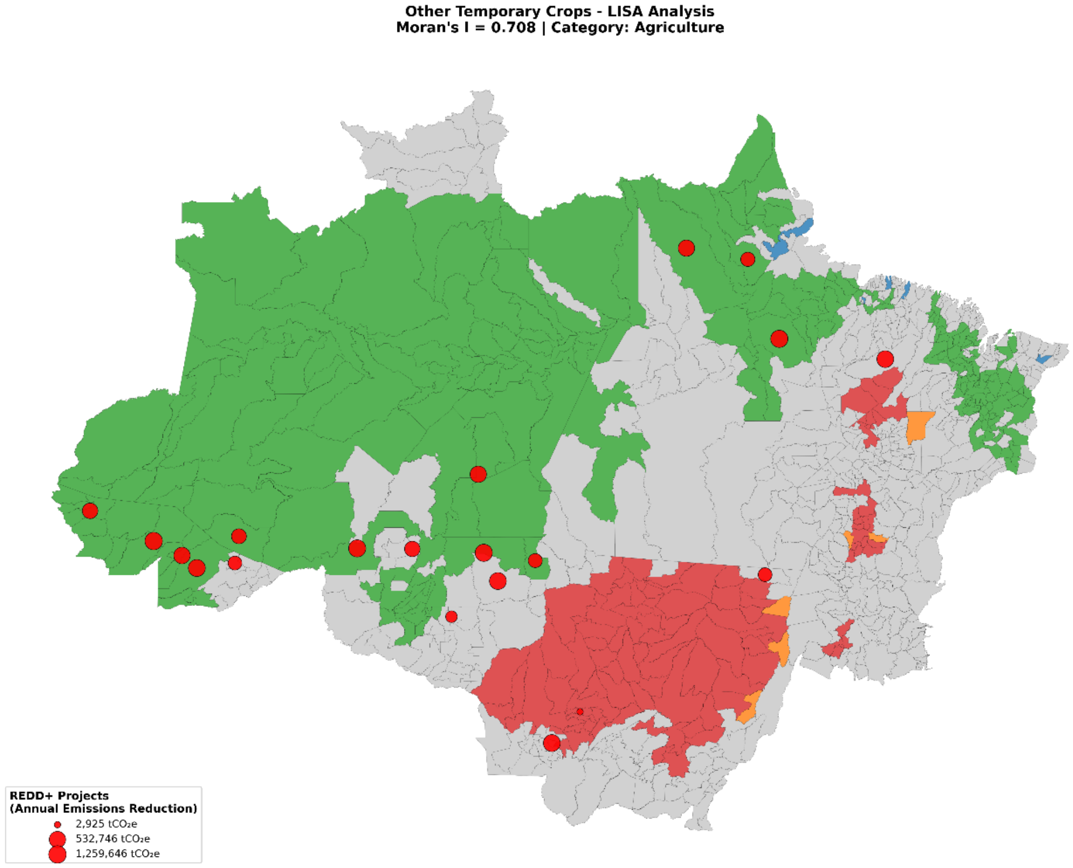

Mangrove - LISA Analysis
Moran's I = 0.650 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

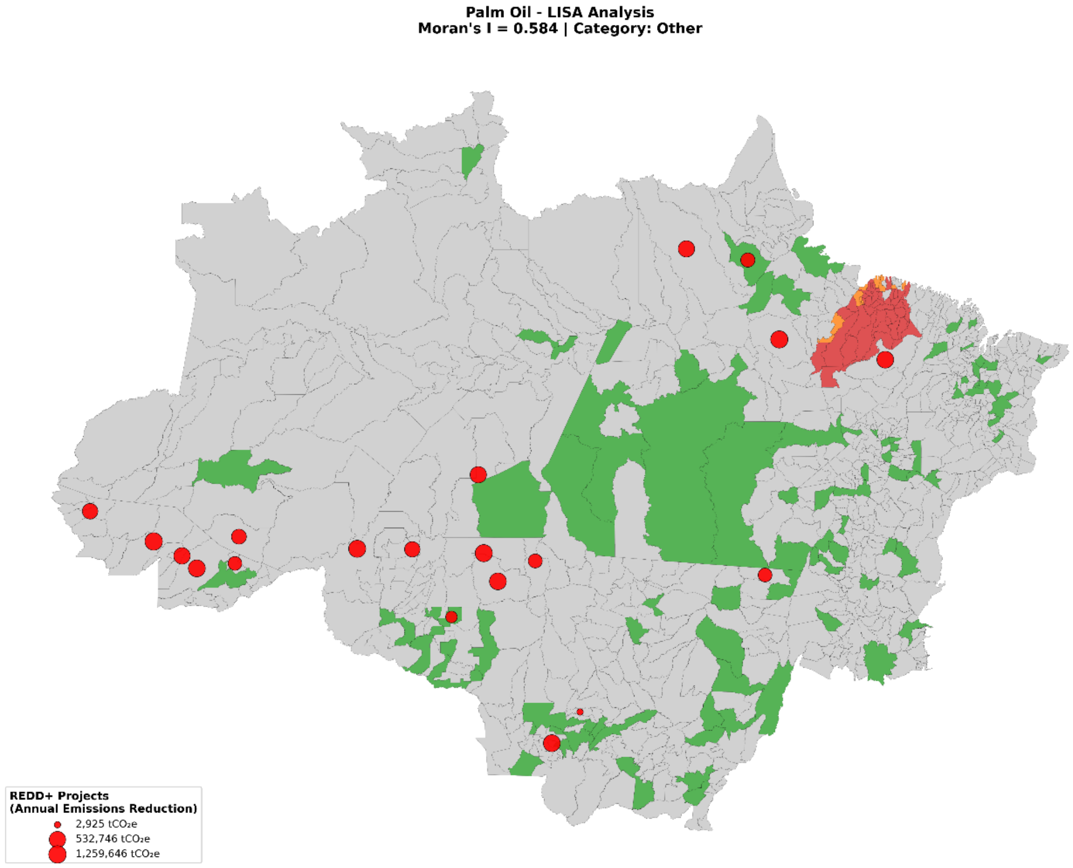

Mining - LISA Analysis
Moran's I = 0.285 | Category: Human Use
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

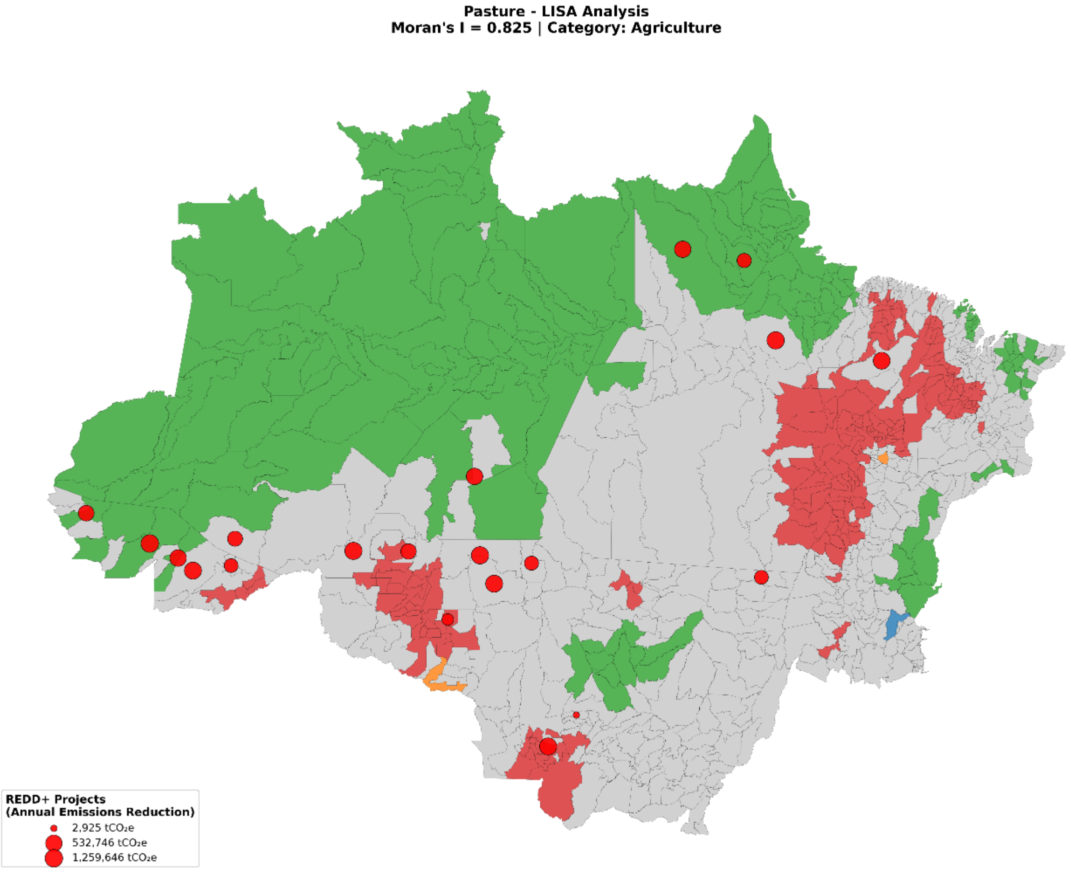

Mosaic of Uses - LISA Analysis
Moran's I = 0.880 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

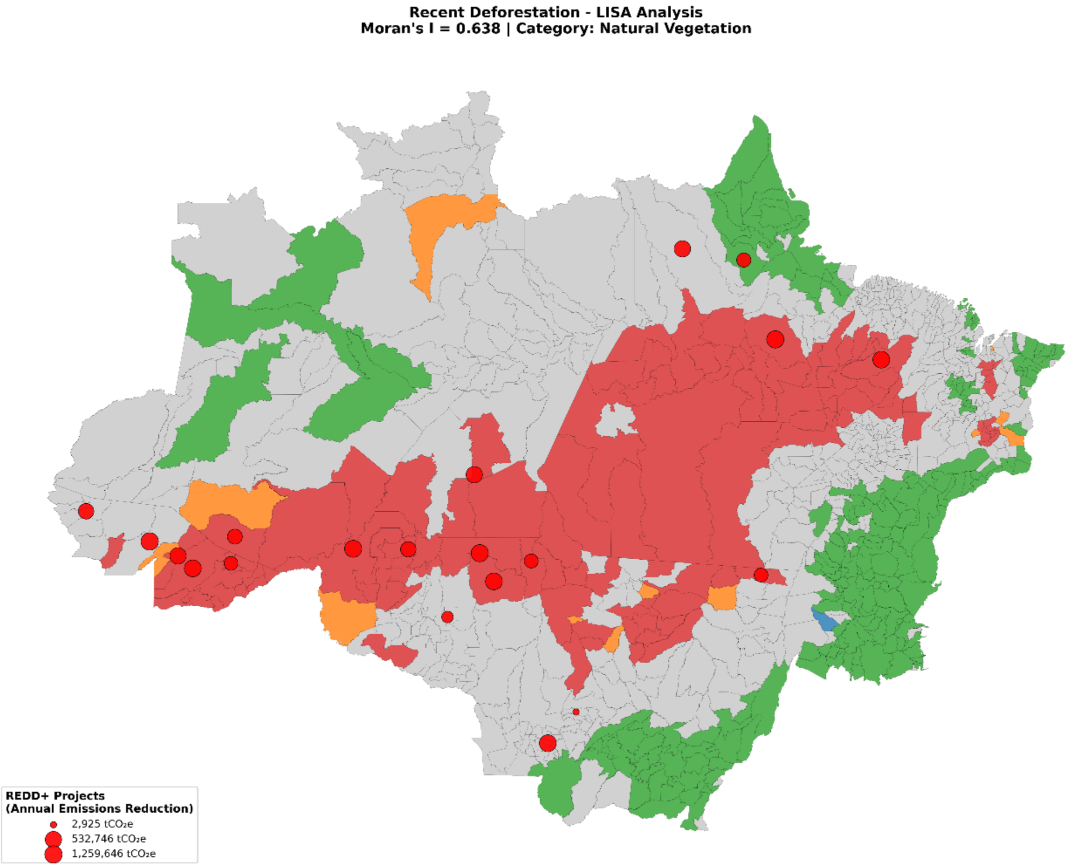

Other Non-Vegetated Areas - LISA Analysis
Moran's I = 0.537 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

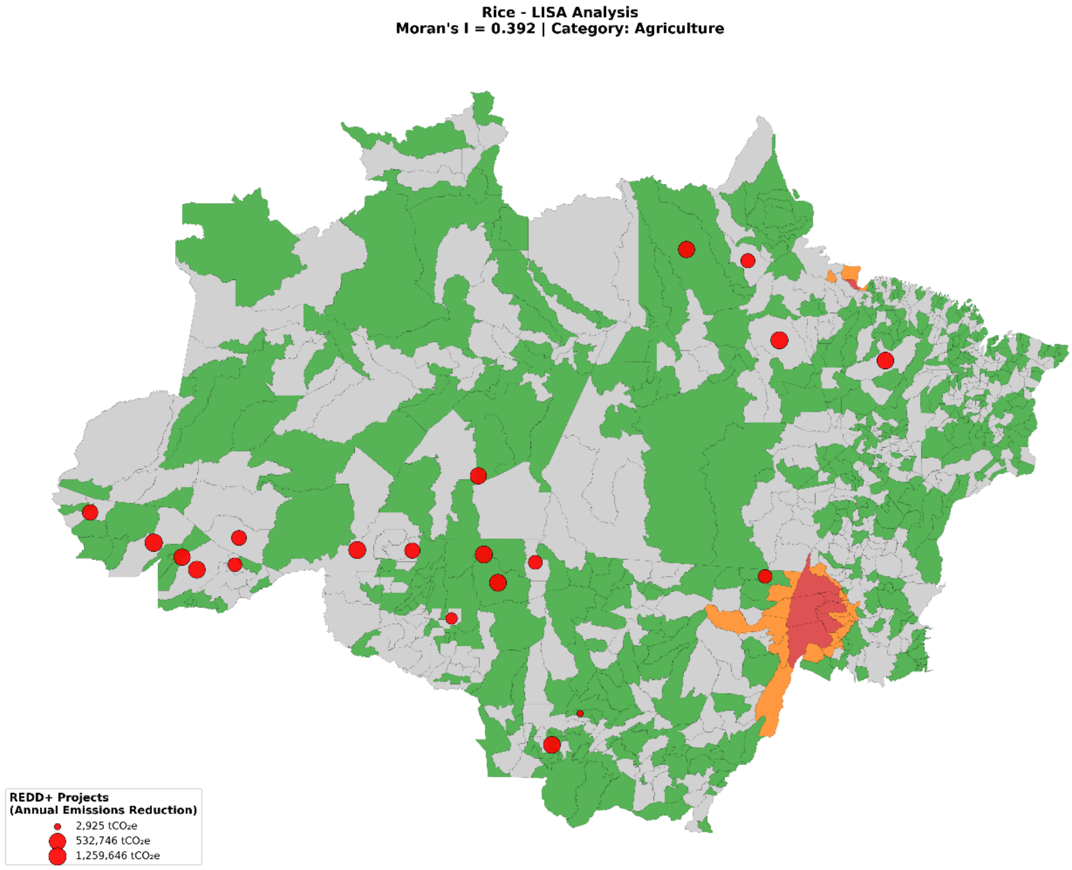
Environmental Management and Sustainable Development
ISSN 2164-7682
2025, Vol. 14, No. 2

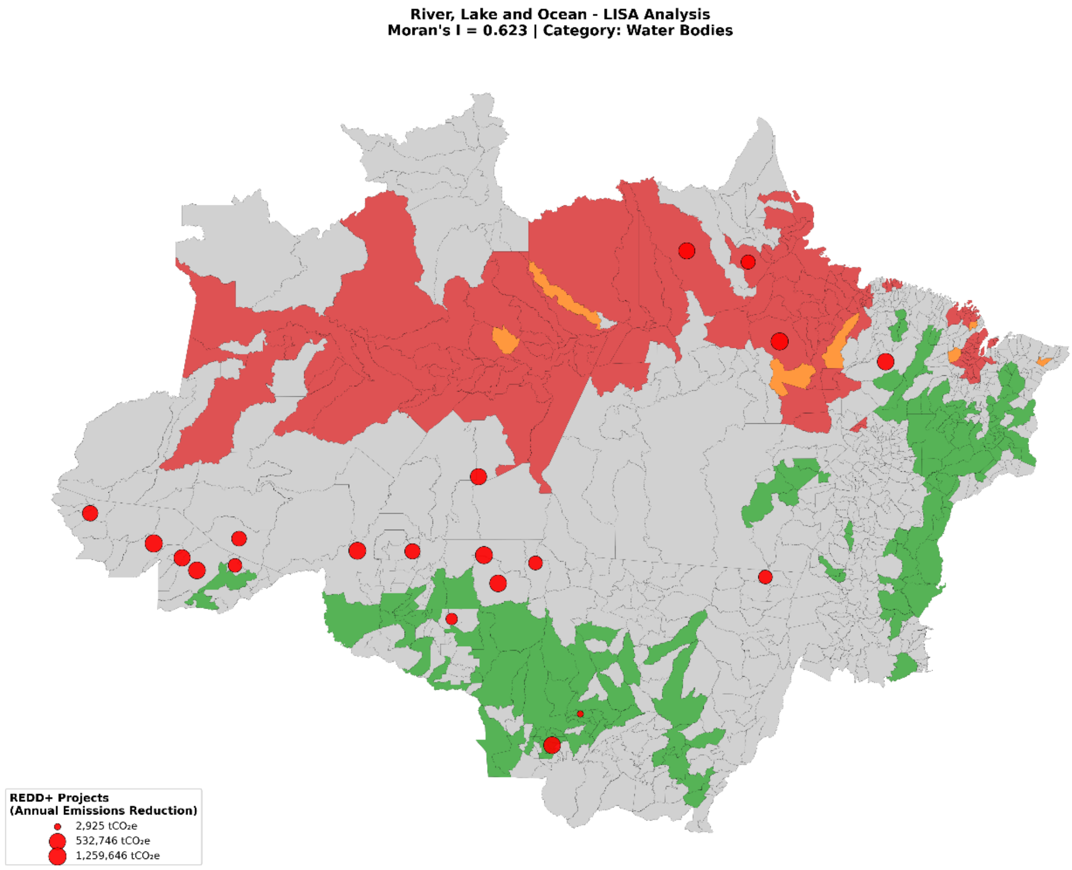


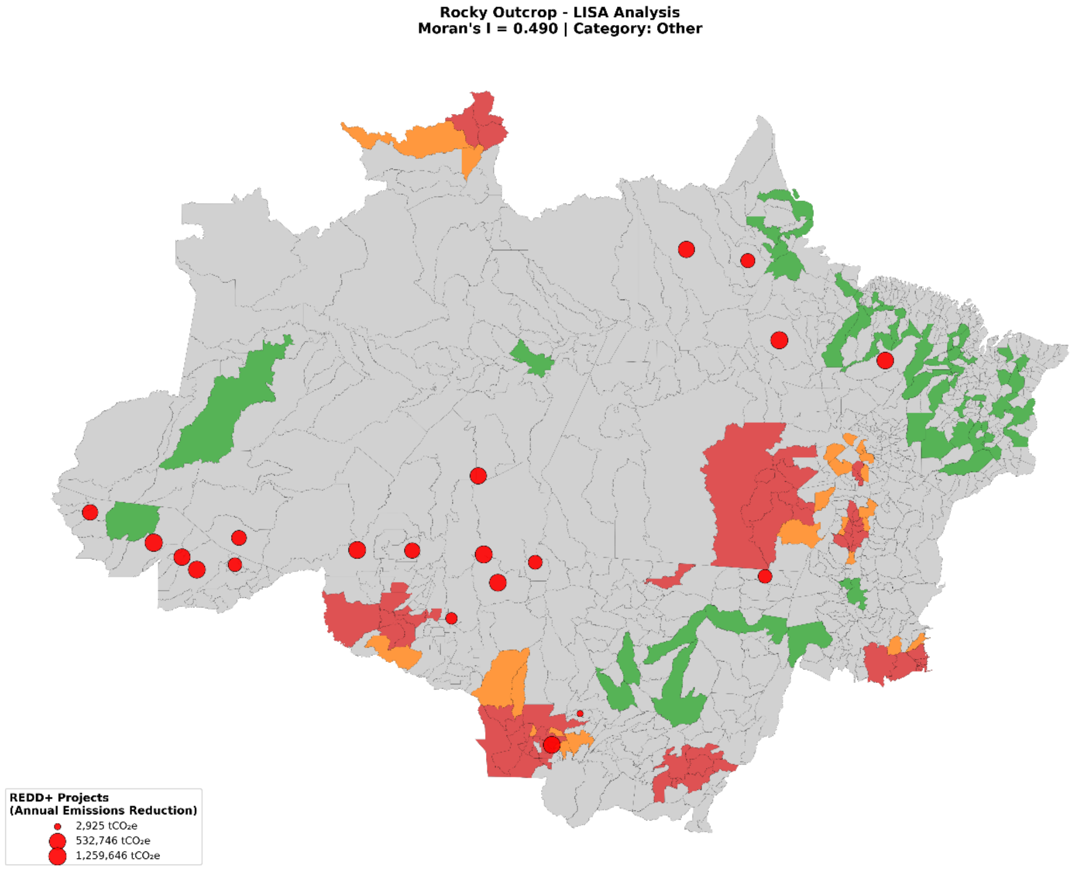


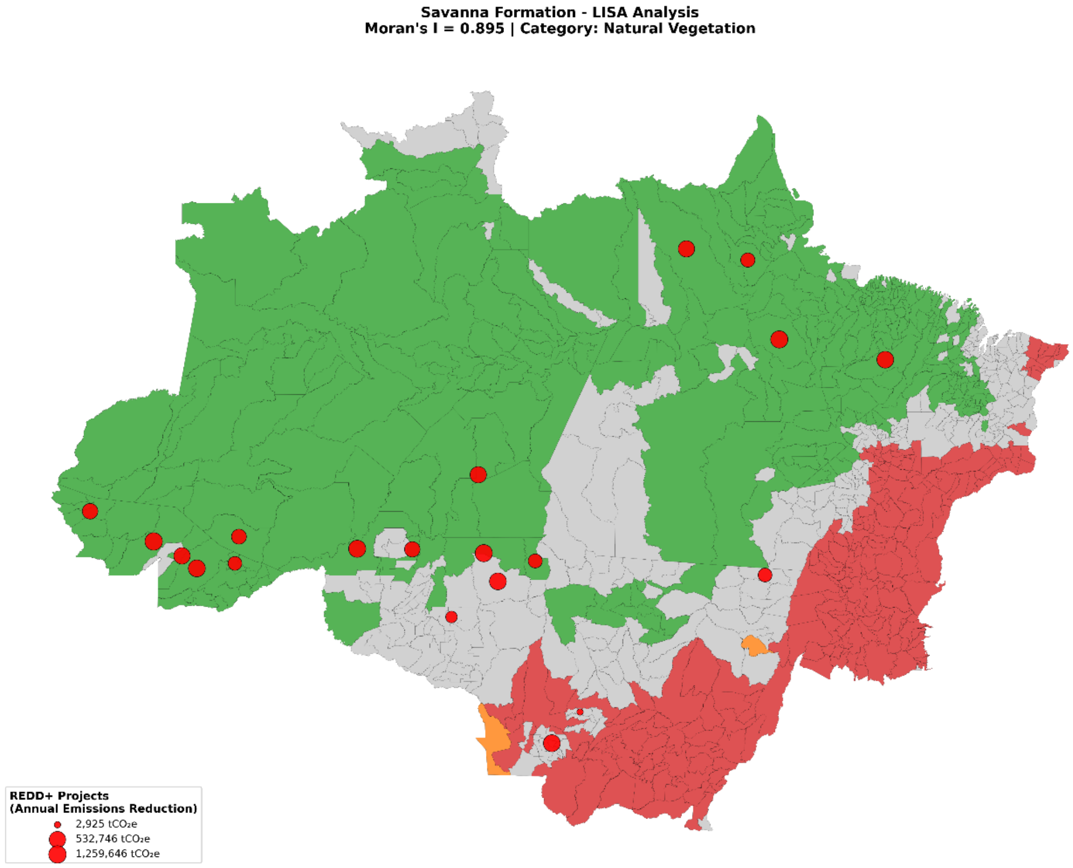

Pasture - LISA Analysis
Moran's I = 0.825 | Category: Agriculture
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

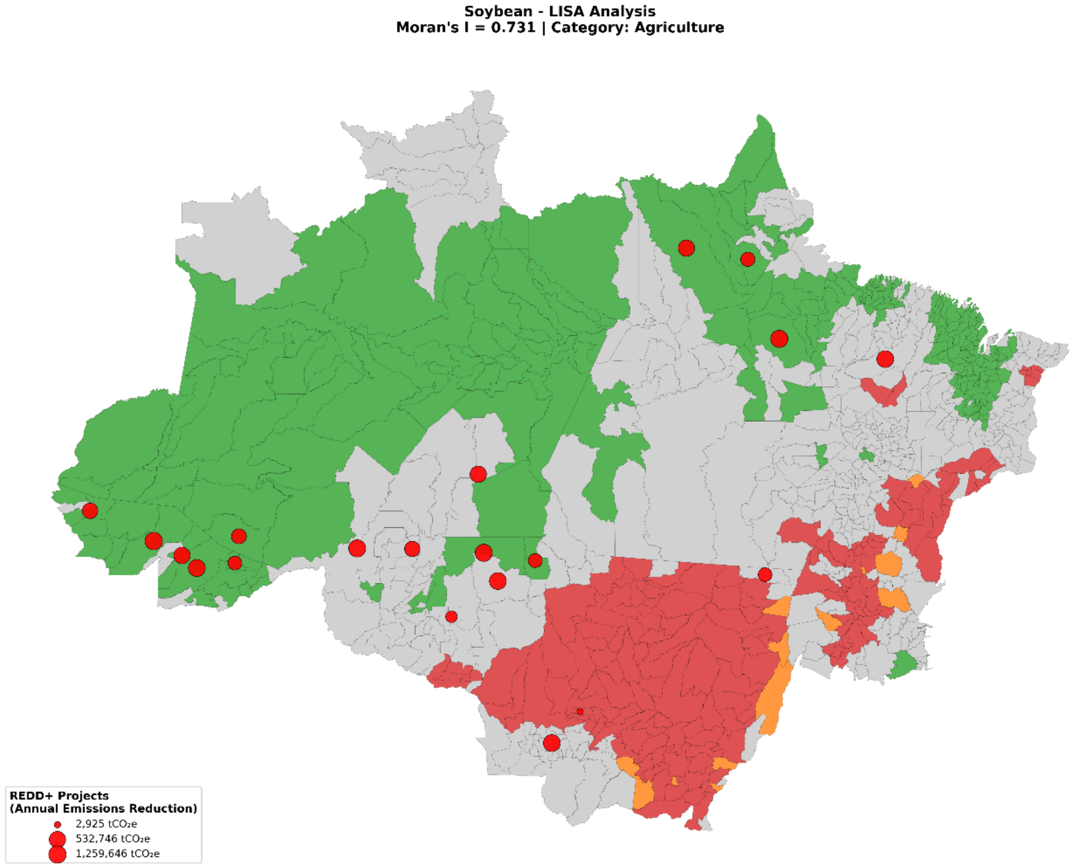

Recent Deforestation - LISA Analysis
Moran's I = 0.638 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

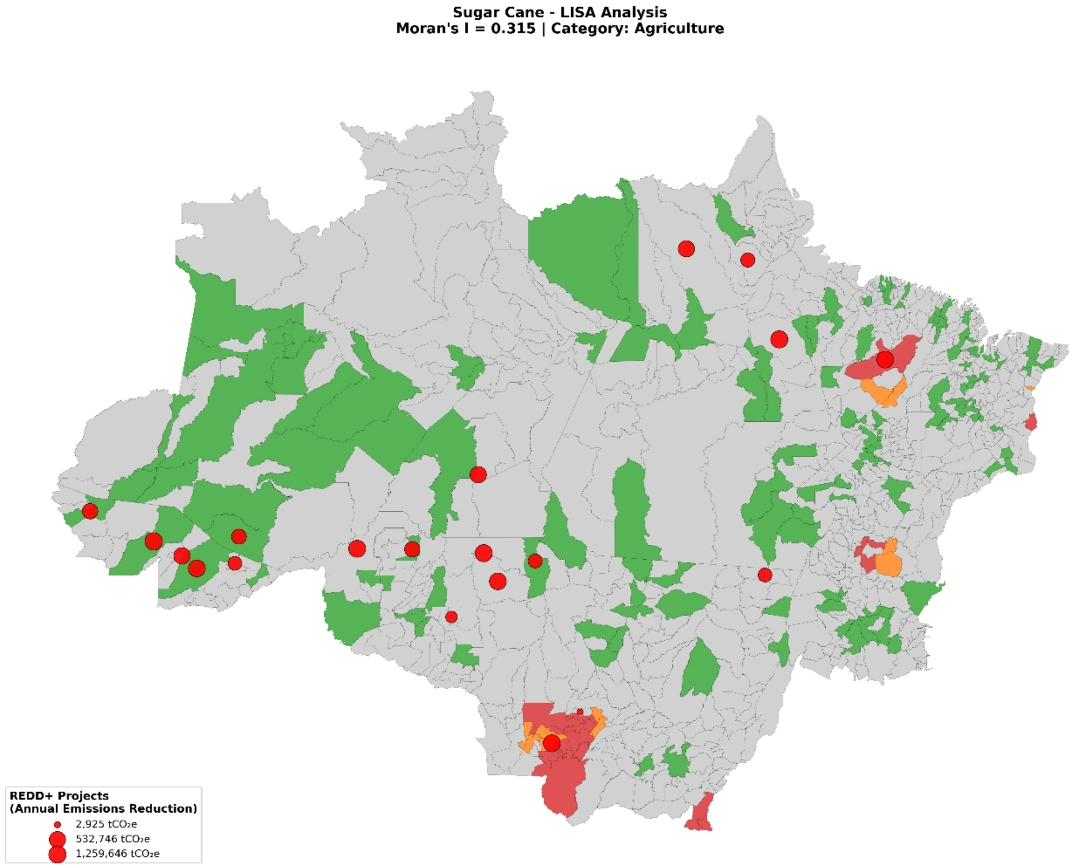

Rice - LISA Analysis
Moran's I = 0.392 | Category: Agriculture
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

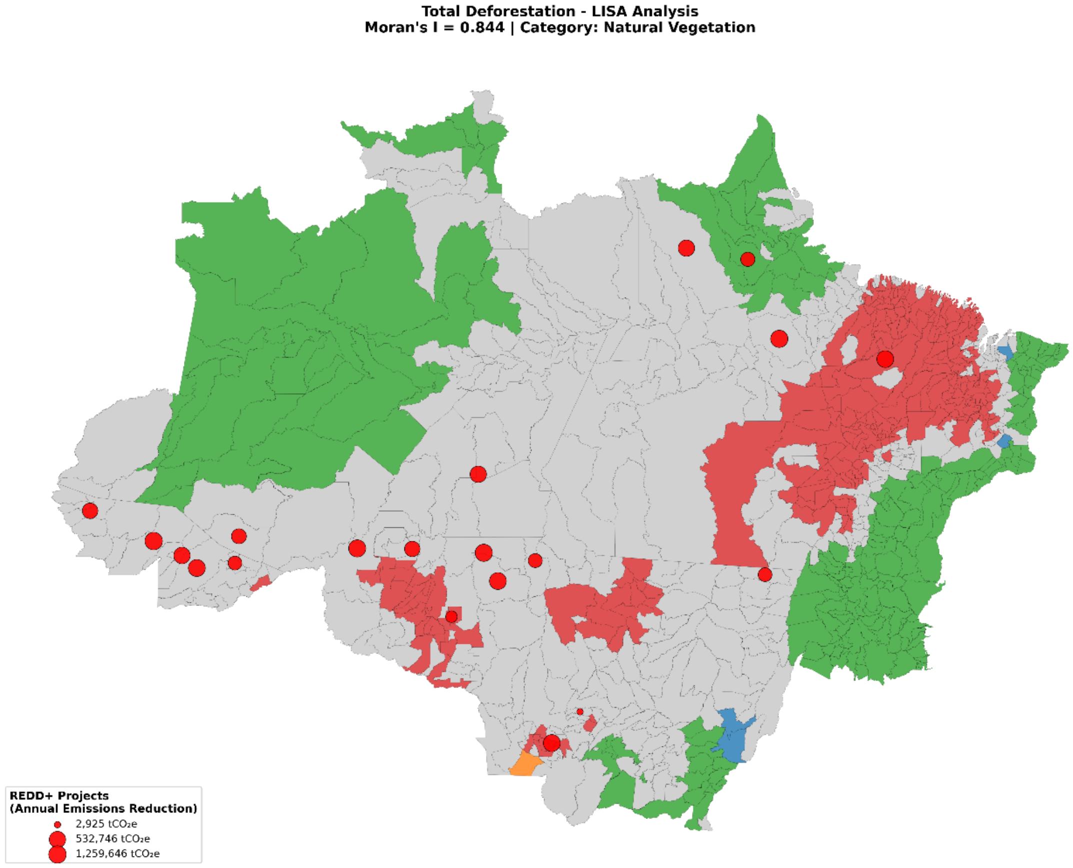

River, Lake and Ocean - LISA Analysis
Moran's I = 0.623 | Category: Water Bodies
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

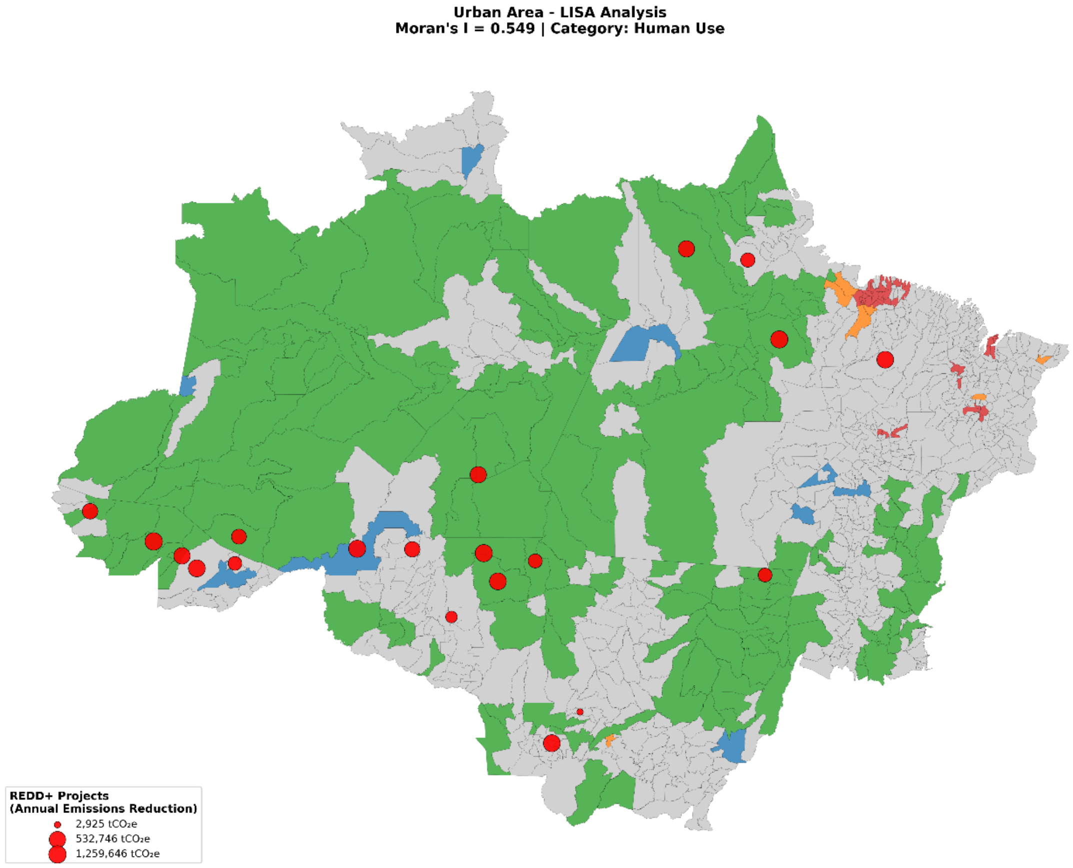

Rocky Outcrop - LISA Analysis
Moran's I = 0.490 | Category: Other
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e

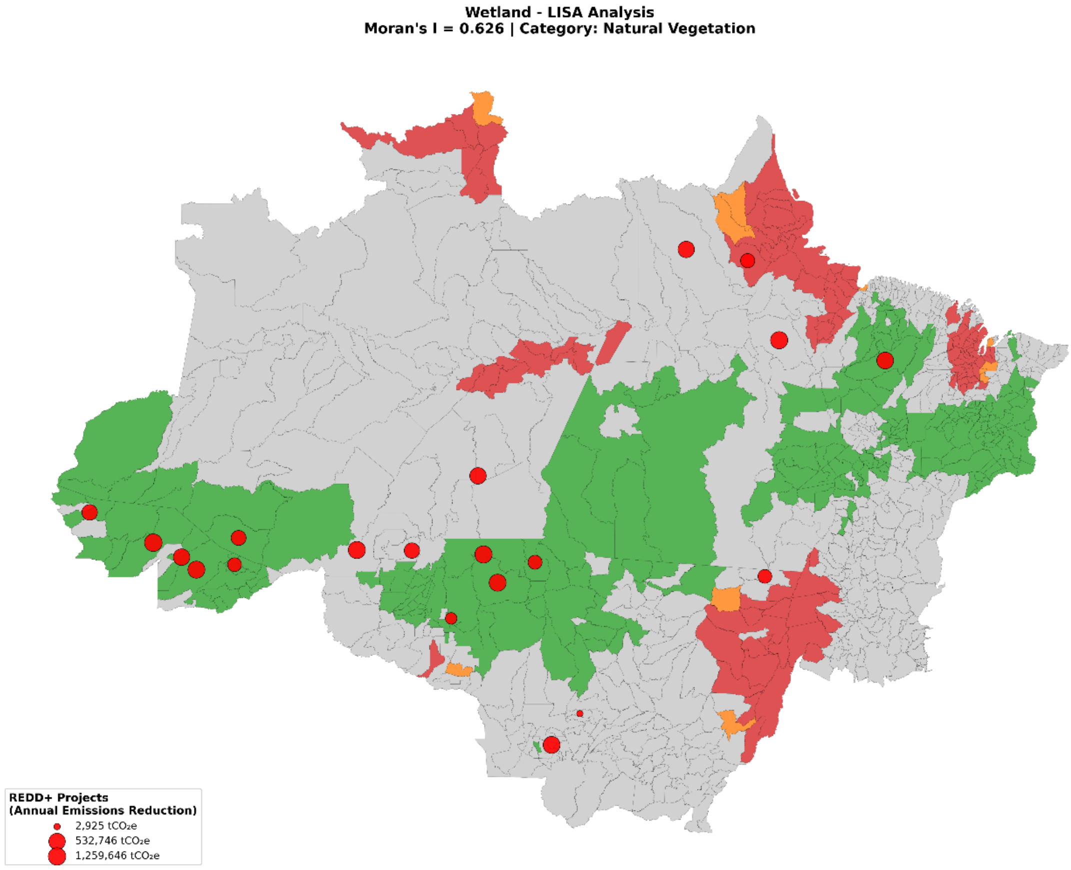

Savanna Formation - LISA Analysis
Moran's I = 0.895 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Soybean - LISA Analysis
Moran's I = 0.731 | Category: Agriculture
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Sugar Cane - LISA Analysis
Moran's I = 0.315 | Category: Agriculture
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Total Deforestation - LISA Analysis
Moran's I = 0.844 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Urban Area - LISA Analysis
Moran's I = 0.549 | Category: Human Use
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e


Wetland - LISA Analysis
Moran's I = 0.626 | Category: Natural Vegetation
REDD+ Projects
(Annual Emissions Reduction)
2,925 tCO₂e
532,746 tCO₂e
1,259,646 tCO₂e