Multiscale Assessment of Agricultural Expansion Potential in Degraded Pasturelands in Brazil Using Geospatial Data

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Abstract

This study aimed to assess the potential for agricultural expansion into pasture areas with varying degrees of degradation in Brazil, providing both quantitative and spatial analyses at different scales – national, biome, microregion, and municipality. The proposed method was based on remote sensing data analysis and on data integration on a geographic information system to map degraded pasturelands, lands with natural agricultural suitability, infrastructure (roads and warehouses), croplands, climate risk agricultural zoning, and legal or environmental constraints posed by indigenous territories, Quilombola communities, agrarian settlements, and conservation units. Results indicate that approximately 28 million hectares of moderately to severely degraded pastures present good to high potential for conversion into croplands, considering the base year of 2022. The Cerrado biome demonstrated the highest potential, accounting for about 14.5 million hectares. The ten municipalities selected by the Digital Agriculture Development Science Center (Semear Digital) initiative and their corresponding microregions presented a total of 34.1 thousand hectares and 266.5 thousand hectares, respectively. The present approach enabled the quantification and spatialization of agricultural potential through a multiscale approach, providing support for decision-making in the formulation of public policies aimed at the restoration of degraded areas.

1. Introduction

Over the past five decades, Brazil's agricultural production has increased significantly due to the growing national and global demand for food, fiber, and bioenergy. Currently, agricultural activities occupy about 33% of the national territory, while native vegetation covers approximately 58% (Souza Jr. et al., 2020; MapBiomas, 2022). Projections indicate that by 2034, the total crop area will reach around 80 million hectares, with an expected production of 380 million tons, representing a 15% increase in planted area and 27% increase in production compared to 2024. In this period, total meat production (beef, pork, and poultry) is expected to increase by 6.8 million tons. Specifically, beef production is projected to increase by 10.2% between 2024 and 2034, with roughly one-quarter of this production intended for export markets (MAPA, 2024). However, concerns about ensuring socioenvironmental sustainability, mainly in areas of degraded grazing lands, have attracted increasing global attention (Costa et al., 2025).

Brazilian pastures cover approximately 177 million hectares, of which 41% show moderate vegetative vigor with signs of degradation, and 21% are classified as severely degraded because of low vegetation vigor (UFG, 2022). Pasture degradation can be analyzed from both agronomic and biological perspectives (Dias-Filho, 2014). Agronomic degradation is characterized by the spread of invasive species and a gradual decline in the land's carrying capacity. Biological degradation involves the loss of soil fertility and structure, leading to the replacement of forage species by plants that grow in poorer soils. In more severe cases, pasture degradation results in bare, exposed soils with no vegetation cover (Louzada et al., 2022).

The economic, social, and environmental impacts of pasture degradation in Brazil are significant. However, accurately detecting and differentiating the varying levels of agronomic and biological degradation using remote sensing techniques remains a major technical challenge (Silva et al., 2024). Given that most Brazilian livestock production occurs on pasture-based systems, monitoring changes in pasture cover is critical, not only for understanding the potential for intensification but also for land-use planning and policy. Despite its importance, spatiotemporal patterns of pasture dynamics in Brazil are still not well understood (Oliveira et al. 2020).

Digital technologies that integrate geospatial data processing and analysis, mainly Geographic Information Systems (GIS) and time series analysis of multisource, multiplatform remote sensing data, are essential for monitoring landscape dynamics and supporting territorial planning (Khanal et al., 2020). In recent years, these technologies have advanced significantly, especially in global land use and land cover (LULC) mapping initiatives such as GlobeLand30 (Chen et al., 2015) and Dynamic World (Brown et al., 2022), as well as national-scale efforts like MapBiomas (Souza Jr. et al., 2020). At the same time, the development of cloud-based platforms for satellite image processing and geospatial data analysis, most notably Google Earth Engine (GEE) (Gorelick et al., 2017), has greatly improved the efficiency, speed, and accuracy of spatial assessments.

In this context, analyses that aims to better understand land use and agricultural dynamics, including expansion, contraction, transition, conversion, diversification, and intensification, are essential. The integration of GIS, remote sensing, and spatial databases is fundamental in deepening spatiotemporal insights into geographic phenomena and their interactions, including variables such as soil, vegetation, topography, hydrography, and geomorphology (Câmara and Medeiros, 1998). Recent studies in Brazil have increasingly focused on improving geospatial analysis to better understand the agricultural dynamics and pasture degradation processes (Bolfe et al., 2024). Accordingly, this study aimed to assess the potential for agricultural expansion

into degraded pasturelands and to produce quantitative and spatial data over multiple scales (national, biome, and municipality levels).

2. Materials e Methods

The methodology employed in this study is based on studies by Victoria et al. (2017) and Bolfe et al. (2024), which identified areas with potential for agricultural production on degraded pasturelands in the Cerrado biome and across the Brazilian territory, respectively.

2.1 Study Area

In this study, we present data generated by Bolfe et al. (2024)for Brazil as a whole, along with quantitative and spatially explicit information for the country's six biomes (Amazon, Caatinga, Cerrado, Atlantic Forest, Pantanal, and Pampa) and for the following municipalities included in the Digital Agriculture Development Science Center – Semear Digital (Embrapa, 2023): Alto Alegre, Caconde, Jacupiranga, Lagoinha, and São Miguel Arcanjo in São Paulo State; Boa Vista do Tupim in Bahia; Ingaí in Minas Gerais; Guia Lopes da Laguna in Mato Grosso do Sul; Breves in Pará; and Vacaria in Rio Grande do Sul (Figure 1). The objective of Semear Digital (Embrapa, 2023), is to connect small and medium size farmers with innovations that have potential to reduce production costs and promote agricultural sustainability.
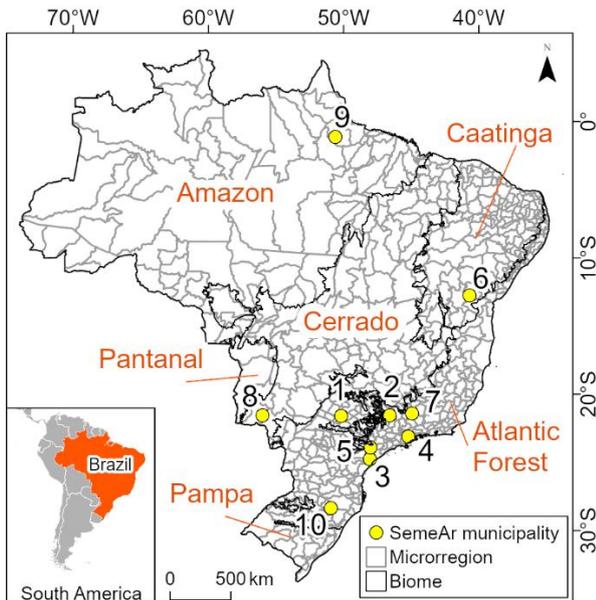

Figure 1. Location of the municipalities that are part of Semear Digital Center in Brazil. (1) Alto Alegre, (2) Caconde, (3) Jacupiranga, (4) Lagoinha, and (5) São Miguel Arcanjo in the São Paulo State; (6) Boa Vista do Tupim in Bahia; (7) Ingaí in Minas Gerais; (8) Guia Lopes da Laguna in Mato Grosso do Sul; (9) Breves in Pará; and (10) Vacaria in Rio Grande do Sul.

2.2 Geospatial Database

The development of the geospatial database involved the acquisition, curation, processing, integration, and analysis of data within a GIS environment, as outlined in Figure 2. The first step of the analysis involved the integration of two key base maps: "Pasture Quality" and "Natural Agricultural Potential of the Land". The "Pasture Quality" data were obtained from the "Pasture Atlas," produced by the Federal University of Goiás (UFG, 2022). In this Atlas, pasturelands across Brazil were classified using time series of the Enhanced Vegetation Index

(EVI), derived from the MOD13Q1product of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor.

These time series were processed using the Temporal Moving Window Median (TMWM) algorithm, which generates stable, gap-filled, and seasonally adjusted data on a pixel-by-pixel basis. Based on a spatiotemporal analysis of normalized EVI values, pasture degradation was categorized into three classes: absent (EVI ≥ 0.6), intermediate ($0.4 \leq$ EVI ≤ 0.6), and severe (EVI $\leq$ 0.4). EVI was selected over the Normalized Difference Vegetation Index (NDVI) due to its lower sensitivity to variations in soil background and atmospheric interference, making it a more reliable indicator for monitoring vegetation conditions.
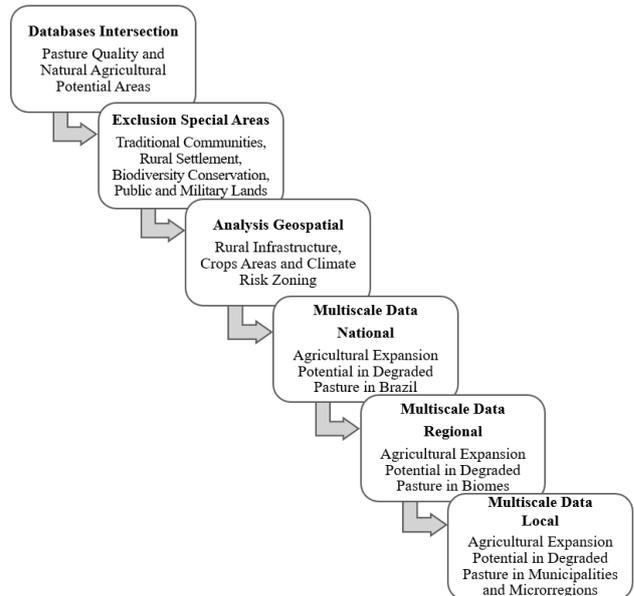

Figure 2. Methodological framework used for analyzing the agricultural expansion potential in degraded pasture in Brazil at multiple levels.

The "Natural Agricultural Potential Map of Brazil's Lands" was developed by the Brazilian Institute of Geography and Statistics (IBGE, 2022) at a 1:250,000 scale. This map classifies land into five categories of agricultural potential or limitations, based on soil and topographical characteristics. The classification includes the following classes: A1 - Very good: deep soils with high fertility and good permeability, located on flat terrains; A2 – Good: soils located mostly on flat terrains, with some restrictions because of the presence of undesirable or harmful ions and relatively shallow soil depth; B – Moderate: soils with moderate fertility restrictions, presence of expansive clays and harmful ions, mostly found on slightly hilly topography; C – Restricted: soils with significant limitations, including shallow depth, expansive clays and harmful ions. They are typically located on rugged terrains, but also can occur in flat areas affected by shallow or fluctuating water tables (hydromorphism); and D - Strongly restricted: soils located on steep slopes, often containing undesirable soluble salts and with severe depth limitations. These areas are primarily designated for environmental protection, conservation, and preservation of native vegetation.

In the second step of the analysis, the following areas were excluded: i) lands belonging to traditional communities, including Indigenous territories (Funai, 2021) and Afro-Brazilian *quilombola* settlements (Incra, 2021a); ii) rural settlements established through agrarian reform programs (Incra, 2021b); iii) federal conservation units (MMA, 2019); iv) areas designated as having very high biological importance for biodiversity

conservation, classified as of very high biological importance (MMA, 2021); v) undesignated public lands, whether under federal or state ownership, not allocated in the National Forest Inventory or recognized by the Brazilian Forest Service (MMA, 2020); and vi) military areas (IBGE, 2017a) (Figure 3).
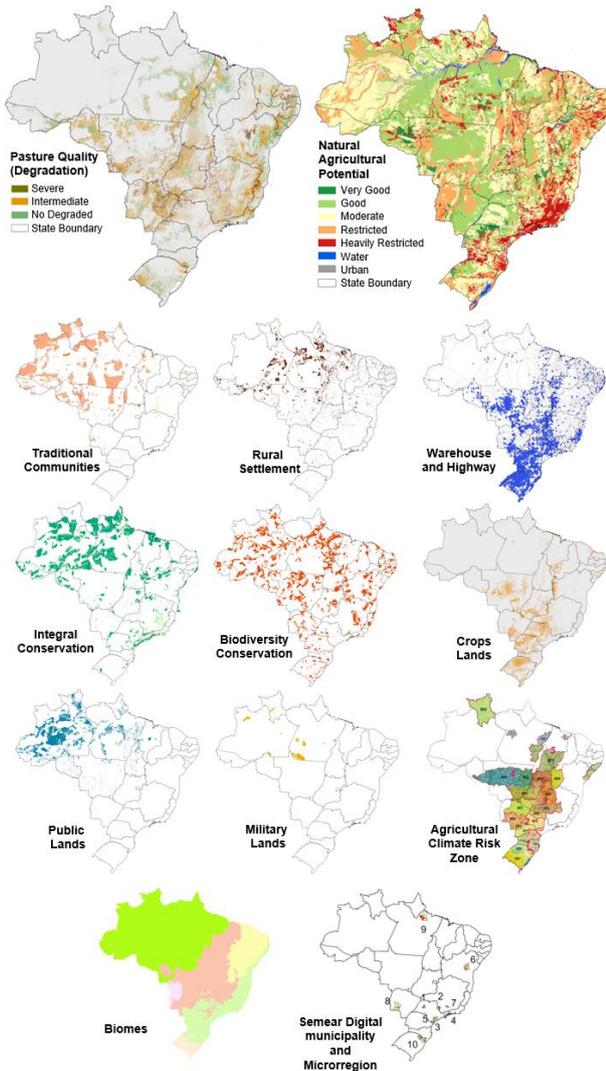

Figure 3. Geospatial databases used for analyzing the agricultural expansion potential in degraded pasture in Brazil.

This study also incorporated several complementary datasets: rural infrastructure, including state and federal highways (DNIT, 2021) and rural warehouses (CONAB, 2023); existing agricultural areas (MapBiomas, 2022); and data from the Climate Risk Agricultural Zoning (ZARC) for the 2022/23 agricultural season (MAPA, 2023).

The ZARC, coordinated by the Ministry of Agriculture and Livestock and the Brazilian Agricultural Research Corporation (Embrapa), assesses climate-related risks to indicate optimal planting windows for rainfed crops. This assessment is based on factors such as local soil water retention capacity, crop coefficients, and regional precipitation patterns. In this study, medium-textured soil and short-cycle crop varieties were used as reference conditions. ZARC identifies a range of annual crops suitable for replacing or integrating with degraded pastures. Crop selection is site-specific and depends on factors such as farm profile, planting dates, soil type, and crop variety. Suitable annual crops include peanuts, rice, oats, cotton, canola, sugarcane, barley, maize, millet, beans, chickpeas, sesame, sunflower, castor bean, soybeans, sorghum, wheat, and triticale. Additionally, various perennial or semi-perennial crops may also be viable, including coffee, pineapple, plums, bananas, cocoa, cashews, citrus, coconut, oil palm, guava, apples, papaya, cassava, passion fruit, watermelon, nectarines, pears, peaches, forage palms, peppers, pupunha, sisal, and grapes. Furthermore, only municipalities with at least 20 days per year in which the probability of planting and harvesting without significant yield loss exceeded 80% were selected.

Finally, the data obtained at the national scale were further processed at two additional geospatial analysis levels: the boundaries of Brazilian biomes (MMA, 2022), microregions and the municipalities (IBGE, 2024) participating in the Semear Digital Center (Embrapa, 2023).

3. Results and Discussion

3.1 Brazilian Territory

According to pasture vigor data from UFG (2022), derived from time series analyses of vegetation indices obtained through remote sensing, 109.7 million hectares of pastures, representing 60% of Brazil´s total pasturelands, exhibit moderate or severe vegetative vigor limitations. Of this total, approximately 28 million hectares of pastures with intermediate or severe degradation are located in areas with high or very high natural agricultural potential, after the regions designated as having high potential for biodiversity conservation or classified as special areas are excluded. Specifically, about 11 million hectares of severely degraded pastures are found in areas with "good" or "very good" agricultural potential, while another 18 million hectares of intermediately degraded pastures are found in similar favorable zones (Figure 4).
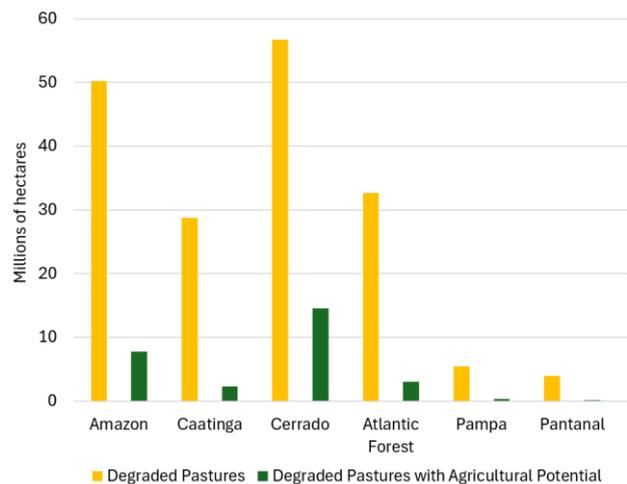

Figure 4. Degraded pastures and agricultural expansion potential in Brazilian biomes.

However, despite the valuable insights provided by pasture vigor assessments, a critical remote sensing methodological challenge remains: distinguishing truly degraded pastures from those that are seasonally dry but still ecologically functional. Misclassifications may occur when spectral indices interpret natural seasonal variations in vegetation cover, especially in biomes with pronounced dry seasons (e.g.. Brazilian Cerrado), as signs of degradation (false positives) (Bolfe et al., 2023). Conversely, short-term vegetative recovery following rainfall

can mask long-term soil and structural degradation, resulting in false negatives. These limitations highlight the importance of incorporating multi-temporal satellite imagery, phenological models, and ground-truth data to refine degradation pasture mapping. Recent studies have emphasized the need for improved classification thresholds and contextual information to reduce misinterpretation and enhance the accuracy of pasture degradation monitoring in Brazil (Pereira et al., 2018; Silva et al., 2024; Bayma et al., 2025).

In a future land use scenario analysis, Soterroni et al. (2019) projected that grain production in Brazil could expand by 2.0 million hectares by 2050. This increase is expected to occur mainly over existing pasturelands and other low-productivity areas, including mosaics of native vegetation and previously converted agricultural lands that are currently underutilized or abandoned.

3.2 Biomes

Regarding the six Brazilian biomes, the potential for agricultural expansion over degraded pastures was observed as follows: 7.7 million hectares in the Amazon, 2.2 million hectares in the Caatinga, 14.5 million hectares in the Cerrado, 3.0 million hectares in the Atlantic Forest, 0.3 million hectares in the Pantanal, and 0.1 million hectares in the Pampa (Figures 4 and 5).
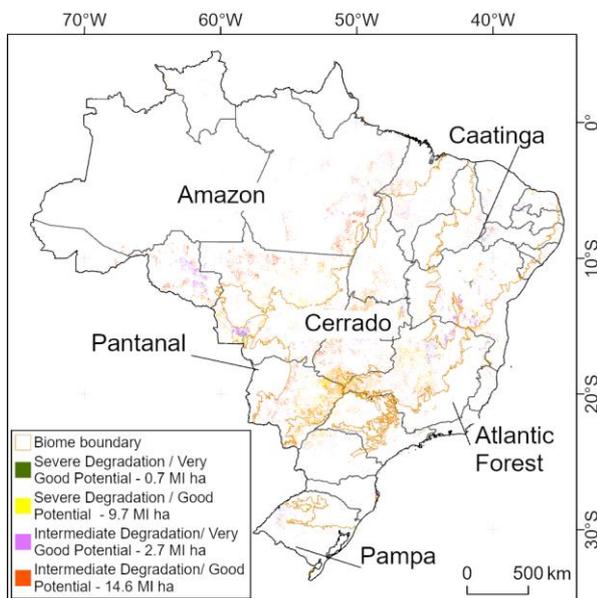

Figure 5. Areas with good to very good potential for agricultural expansion over Brazilian pasturelands presenting intermediate to severe degradation.

The Cerrado biome, with 56.6 million hectares, has the largest concentration of degraded pastures in Brazil, which corresponds to approximately 32% of the country´s degraded pasture areas. Pasture degradation in the Cerrado is a complex process driven by a combination of agro-environmental conditions and land management practices. In a study focused on this biome, Oliveira et al. (2020a) found no correlation between the technological index and the pasture degradation index, suggesting that degradation can occur even in extensive cattle production systems where low levels of technology are applied (Louzada et al., 2022).

3.3 Microregion and Municipality

Among the ten microregions encompassing the municipalities selected as study areas by the Semear Digital Center, eight presented degraded pasture areas with high or very high potential for agricultural expansion (Table 1). The Bodoquena microregion, which includes the municipality of Guia Lopes da Laguna (MS), presented the largest area of degraded pastures with agricultural potential, totaling 145.7 thousand hectares. In contrast, the Registro microregion, which includes Jacupiranga (SP), presented the smallest area, with only 11.7 hectares. The Birigui microregion, SP, showed the highest percentage of such high potential areas (8.36%) (Figure 6).

Microregion	Municipality	State	Potential for Expansion	
			Area (ha)	%
Registro	Jacupiranga	SP	11.7	0.00
Piedade	São Miguel Arcanjo	SP	973.5	0.23
São João da Boa Vista	Caconde	SP	8,075.4	1.49
Vacaria	Vacaria	RS	17,474.2	1.01
Lavras	Ingaí	MG	23,444.9	6.81
Itaberaba	Boa Vista do Tupim	BA	33,119.7	2.01
Birigui	Alto Alegre	SP	37,706.3	8.36
Bodoquena	Guia Lopes da Laguna	MS	145,787.2	6.45
		Total	266,592.9	–

Table 1. Potential for agricultural expansion over degraded pasture in microregions encompassing municipalities selected by Semear Digital Center. State: SP = São Paulo; RS = Rio Grande do Sul; MG = Minas Gerais; BA = Bahia; MS = Mato Grosso do Sul.

Regarding the municipalities selected by the Semear Digital Center, the potential for agricultural expansion in degraded pastures was identified as follows (Figure 6): 17,405 hectares in Guia Lopes da Laguna (MS), 7,721 hectares in Vacaria (RS), 5,464 hectares in Boa Vista do Tupim (BA), 2,831 hectares in Ingaí (MG), 789 hectares in São Miguel Arcanjo (SP), and 51 hectares in Alto Alegre (SP), with a total of 34,621 hectares.

Figure 7 shows examples of areas with different levels of pasture degradation in the municipality of Guia Lopes da Laguna (MS), located in the Brazilian Cerrado. An effective land use strategy for this region is the adoption of Crop-Livestock-Forestry Integration System (ILPF). Oliveira et al. (2024) highlighted that such systems have been increasingly adopted in this region, demonstrating high plant and animal productivities and significant soil C accumulation. These benefits make ILPF a key strategy for intensifying agricultural production in the Brazilian Cerrado, while promoting rural sustainability. The authors also emphasized that integrated practices contribute to the restoration of degraded pastures, support both livestock and grain productions, and help prevent further deforestation of native vegetation.
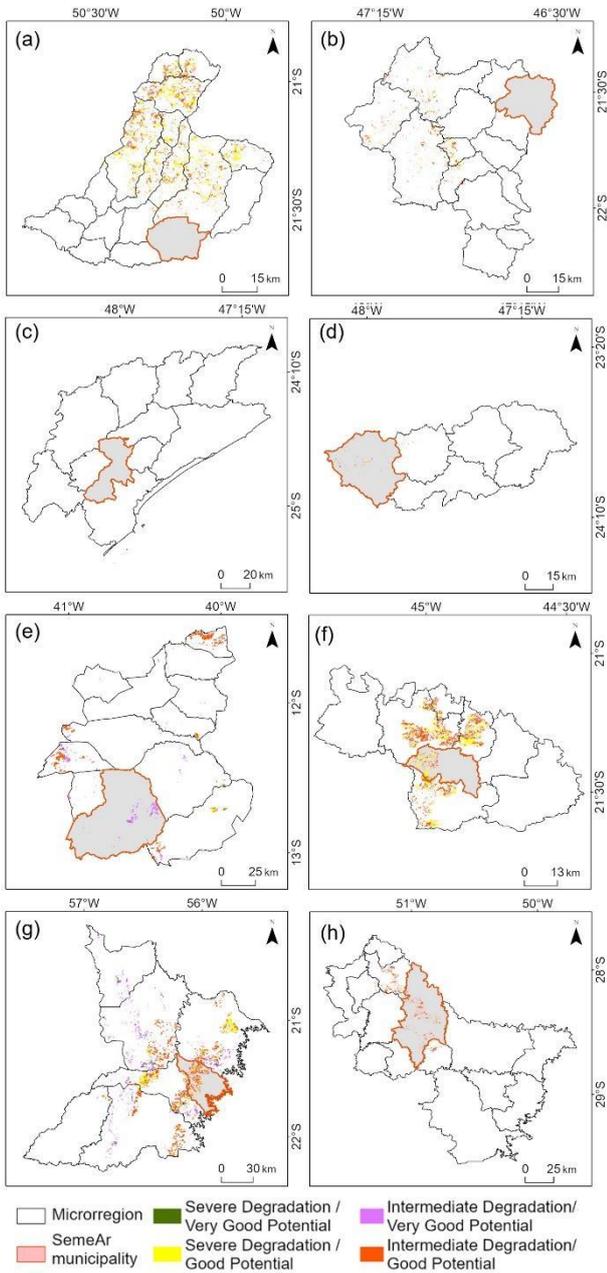
Figure 6. Potential for agricultural expansion over degraded pastures in the municipalities selected by Semear Digital Center. (a) Birigui, (b) São João da Boa Vista, (c) Registro, and (d) Piedade in São Paulo State; (e) Itaberaba in Bahia State; (f) Lavras in Minas Gerais State; (g) Bodoquena in Mato Grosso do Sul State; and (h) Vacaria in Rio Grande do Sul State.

3.4 Rural Development Planning

In this study, the integration of multiple data layers within a GIS environment allowed the mapping of severely and moderately degraded pastures with potential for conversion to crop production at different scales. Our results are, to some extent, consistent with the data produced by the 2017 Agricultural Census (IBGE, 2017b), which reported the existence of 12 million hectares of pastures in "poor condition" in Brazil. Our study also demonstrated that the organization, integration, and analysis of spatial data are becoming increasingly important for generating detailed, high-quality, and accurate information to support sustainable rural development planning.

Figure 7. Field photos of pasturelands in the Mato Grosso do Sul State. (a) degraded pasture in Guia Lopes da Laguna – 2024; (b) non-degraded cultivated pasture in Guia Lopes da Laguna – 2024; and (c) livestock-forestry integration in Campo Grande – 2023.

In beef cattle production systems, the evaluation of novel approaches and metrics for assessing pasture-based animal productivity is essential. Enhancing both production efficiency and sustainability depends on robust, science-based evidence to support private decision-making by stakeholders and to assist the formulation of effective public policies (Martha Jr. et al., 2024). Despite methodological differences among initiatives such as those led by IBGE and MapBiomas, a consistent finding is that a vast area of agriculturally suitable land is currently occupied by degraded pastures. This highlights the importance of leveraging all available data sources, including the synergistic use of multi-sensor remote sensing technologies and the integration of spatial data with historical statistics from censuses and survey-based research (Weiss et al., 2020). Land degradation and climate change continue to pose serious threats to global food security and rural sustainability.

4. Conclusions

This study identified approximately 28 million hectares of degraded pastures in Brazil with potential for agricultural expansion. Among these areas, 2.5% are classified as severely degraded with very high agricultural potential, 35% as severely degraded with good potential, 9.8% as moderately degraded with very high potential, and 52.7% as moderately degraded with good potential. The Cerrado biome holds the highest potential, encompassing 14.5 million hectares.

Among the ten municipalities selected by the Semear Digital Center, the municipality of Guia Lopes da Laguna (MS), located in the Bodoquena microregion, stood out with 145.7 thousand hectares of degraded pasture with agricultural potential. This result demonstrates the relevance of degraded pasture areas in the context of Brazilian land use and land cover.

The multiscale approach employed in this study enabled the quantification and spatialization of agricultural potential, providing valuable insights to support public policies and land use planning at municipal, regional, and national levels.

Among the priorities for future research, a key challenge is the refinement of pasture degradation mapping by considering spectral index thresholds adapted to regional agro-environmental conditions. Equally important is the integration of databases containing socioeconomic information on areas currently undergoing pasture recovery, which can support targeted interventions. In addition, future studies could incorporate other datasets and references focused on the spatiotemporal analysis of pasture degradation in Brazil over the past decades.

Acknowledgements

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