

Article

Potential for Agricultural Expansion in Degraded Pasture Lands in Brazil Based on Geospatial Databases

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Abstract: Important public and private initiatives to map agricultural lands and natural resources have been carried out in Brazil to support land use planning. Some studies indicate that Brazil still has up to 109.7 million hectares of cultivated pastures with some level of degradation, representing around 60% of the total pasturelands, estimated at 177 million hectares. This study aimed to gather, process, and analyze publicly available databases to generate quantitative and spatial information about the potential of Brazilian degraded pastures for agricultural expansion. We considered data related to the natural agricultural potential, restrictions imposed by special areas (indigenous lands and Afro-Brazilian “quilombola” settlements), areas with high biodiversity conservation priorities, infrastructure such as distance between major highways and availability of warehouses, current agricultural areas, and the information made available by Agricultural Climate Risk Zoning. The results indicated the existence of approximately 28 million hectares of planted pastures with intermediate and severe levels of degradation that show high potential for agricultural crops. These areas could increase the planted areas with grains in Brazil by approximately 35% in relation to the total area used in the 2022/23 crop season.

Keywords: spatial analysis; land use planning; digital agriculture; GIS



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1. Introduction

The Organization for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO) predict a global increase in food demand by more than 13% until 2032 (about 1.3% increase per year), mainly as a consequence of world population growth, estimated to increase from 7.9 billion in 2022 to 8.6 billion in 2032 [1]. This prediction is accompanied by uncertainties in global food security because of geopolitical issues, adverse climate change, animal and plant diseases, and rising agricultural input costs in recent years.

Brazil is a major producer and exporter of agricultural commodities, and has contributed to more sustainable production by increasing productivity and implementing systems such as the no-till agriculture, integrated crop-livestock-forestry (ICLF), and agro-forestry. In the last four decades, Brazilian crop production has increased by around 600%, while the planted area has increased by only approximately 100% [2]. Currently, the country has 33% of its territory occupied by agricultural activities and 58% by native vegetation cover [3,4]. The Ministry of Agriculture, Livestock, and Supply estimates that grain production in Brazil will reach 390 million tons in the 2032/33 harvest, an approximate increase of

24% over the 2022/23 harvest [5]. This prediction is based on an increase in both agricultural productivity and planted area, which should go from the current 77 million hectares to about 92 million hectares. In addition, beef, pork, and poultry production may grow by 22%, from the current 29 million tons to 36 million tons by 2032/33. However, there is a growing concern among consumers and public and private organizations regarding greater environmental sustainability, especially in pasture fields.

Most of the livestock activities deal with raising ruminants (cattle, sheep, and goats) in which their main food source is either native or cultivated pastures. The terms “pasture” and “rangeland” are commonly used to indicate areas that have been modified by animal production, namely grazing [6]. The Food and Agriculture Organization of the United Nations (FAO)’s definition of pasture is “...the land used permanently (for a period of five years or more) for herbaceous forage crops, either cultivated or naturally growing” [7]. In this study, native grasslands commonly used for cattle raising were not included in the analysis. The main grass species found in Brazil are the African *Brachiaria*, *Panicum*, and *Andropogon* genus due to their easy adaptation to the country’s very diverse climate and soils. They are primarily used for cattle raising. In Brazil, most of the goat and sheep herds are found in the northeast of Brazil, mostly for local consumption.

Brazilian pastures cover approximately 177 million hectares, of which 41% have medium vegetative vigor and signs of degradation, while 21% have low vegetative vigor, understood as severe degradation [8]. Historically, the land occupied by cultivated pastures in Brazil is biome specific. In the northern (Amazonia, tropical rainforest) and central (Cerrado, tropical savanna) parts of the country, exotic species of pastures, mostly the African *Brachiaria* (and *Andropogon* species if the soils are rocky), are seeded right after the slash-and-burn type of native vegetation suppression [9]. The pastures are mainly for cattle beef production, and it is quite common to find several large farms in this region (>500 hectares). In the western (Pantanal, wetlands) and southern (Pampa, grasslands) parts of the country, native pastures are mostly used for cattle beef production [10]. In the coastal part of the country (Atlantic Forest), the farms are predominantly small, the pastures (mostly *Panicum* species) present high biomass productivity, and most of the national milk production is found in this region [11]. The cultivated pastures in the Northeast (semi-arid Caatinga) face serious problems in forage production due to the shortage in rainfall [12].

The past and current expansion of cattle ranching in Brazil is basically driven by the accessibility of lands to be incorporated into meat production, and the expected development of a transportation system and markets related to products, inputs, and labors in the region [13]. Other factors are the growth of national and international demand for cattle beef, and investments in the construction of roads. In the decades of 1950 and 1960, most of Brazilian cattle ranchers focused on a market little-demanding in terms of quality, and the expansion occurred in native pastures and cultivated pastures with low levels of farm management. In the following decades, we faced a substantial improvement in animal genetics and forage production. It is quite unusual seeing pastures replacing croplands in Brazil; however, the crop-livestock integration system has been largely adopted nowadays, mainly in the Cerrado and in the Cerrado—Amazon ecotone regions.

An estimated 20% of the world’s pastures are losing productivity due to degradation and/or inadequate management [14]. Degradation is the main cause of loss in pasture quality in countries where herds are grass-fed [15]. The factors responsible for pasture degradation in the world are diverse, though overgrazing is reported as the leading cause [16]. The reduction of forage production due to global climate change (shortage of rainfall and increase of temperature) is another important cause of pasture degradation [17]. The decrease and aging of people living in rural settlements consequently reduces the efficiency of farm management, and is another cause of pasture degradation. The Brazilian pasture degradation can be analyzed from an agronomic and biological point of view [18]. In the agronomic degradation concept, there is an increase in weed infestation, gradually decreasing the pasture-carrying capacity. In the biological degradation concept, the soil loses its ability to sustain plant production, leading to the gradual replacement of forage by plants with

lower soil fertility demand, or simply to the appearance of areas devoid of vegetation (bare soil). Thus, in pastures formed in regions where the dry season is not so severe, typically in the Brazilian Amazon, agronomic degradation is predominant and is related to poor farm management, while in places where the climate is drier, for example, in the Cerrado biome, the biological degradation is predominant and is related to poor farm management and overgrazing. The definition and estimate of the total area of degraded pastures, or pastures with some indication of degradation in Brazil, vary according to the methodology used by different sources. For example, Strassburg et al. [19] reported that the productivity of Brazilian cultivated pasturelands is 32–34% of its potential. Dias-Filho [18] emphasized that degraded pastures constitute one of the major problems of national livestock production, being defined as those pastures that present a sharp decrease in productivity potential or ideal carrying capacity, and may or may not have lost the capacity to maintain biological productivity or biomass accumulation.

Pasture degradation is usually related to overgrazing, insufficient weed and pest control, and lack of soil fertilization [20]. The Brazilian degraded pastures can be seen as potential areas for agricultural expansion, since their restoration by ranchers is difficult because of the relatively high costs of chemical fertilizers compared with the average price of cattle beef, meaning that it may take several years to recover the investment made [21]. On the contrary, the correction of soil fertility and soil acidity by grain and biofuel producers to increase productivity has been worthwhile in terms of the cost–benefit relationship. Previous studies have demonstrated that crop–pasture rotation is a good alternative for better use of degraded pastures. For example, Sekaran et al. [22] pointed out that integrated crop–livestock systems play a key role in the functioning of the farms by increasing the animal sources of food. Other advantages reported in the literature are related to improved crop productivity, reduced pressure for opening new areas for food and energy production, enhanced carbon sequestration, the reduction of the application of chemical fertilizers, and control of soil erosion, among others (e.g., [23,24]).

Considering Brazil's high international prominence in the production of food, fibers, and agro-energy, it is essential to generate analyses and studies aimed at a better understanding of the agricultural dynamics, which involves expansion, retraction, transition, conversion, diversification, and agricultural intensification. Digital technologies involving geospatial data processing and analysis using geographic information systems (GIS) and time series analysis of multisource and multiplatform remote sensing data are essential to monitor these dynamics and to support territorial planning [25]. These technologies are marked by significant advances in recent years at both global and national scales, for example, the cloud computing capabilities of the Google Earth Engine (GEE) [26], and the different initiatives of land use and land cover (LULC) mappings, such as the Dynamic World [27], GlobeLand 30 [28], and MapBiomass [3]. However, due to the complexity of the Brazilian rural environment, there is a growing need for new studies that involve the integration of different geospatial databases from distinct sources and a different range of geographical scale, such as those conducted by Parreiras et al. [29–31].

The agricultural intensification in Brazil has become a strong desire of national governments, for example, to increase its gross domestic product [32]. Such intensification can be obtained by opening new areas of native vegetation, which is strongly not recommended because of environmental issues, or by adopting crop–livestock integration systems on pasturelands [33]. Another option is to expand crop production in cultivated pastures with different levels of degradation, since recovering degraded pastures is costly and timely. However, not all degraded pastures will be suitable for crop production, since extensive and rainfed crop production depends strongly on climate, soil, topography, and infrastructure such as the availability of roads and warehouses, among other aspects.

This study can be considered as a follow-up of the previous study conducted by Victoria et al. [34], who indicated suitable areas for crop production in degraded pastures of the Brazilian Cerrado. Our study expands the study area to the entire country, and adds more layers in the spatial data analysis. To our best knowledge, there are no studies in

Brazil mapping different levels of suitability of degraded pastures for crop production at the national level. Within this context, this study aimed to produce spatial data on the potential for agricultural expansion over pasture fields with some degree of degradation in Brazil, based on analyses carried out in a GIS environment. Such expansion will assist in meeting the global food demand without increasing the suppression of native vegetation and by reducing soil erosion associated with degraded pastures.

2. Materials and Methods

The methodology used in this study was based on the analysis of different LULC maps, topography, climate, soils, and protected areas, similar to the previous studies conducted for the Brazilian Cerrado (tropical savanna) [34,35]. In the late 1990s, GIS analysis gained importance because of its capability of dealing with the spatio-temporal analysis of geographical phenomena or with the relationships between different phenomena to identify, for example, different thematic classes of agricultural zoning, based on aspects such as soil, vegetation, and geomorphology [36]. The methodology adopted in this study involved the acquisition, curation, processing, integration, and analysis of databases in a GIS environment (Figure 1; Table 1).

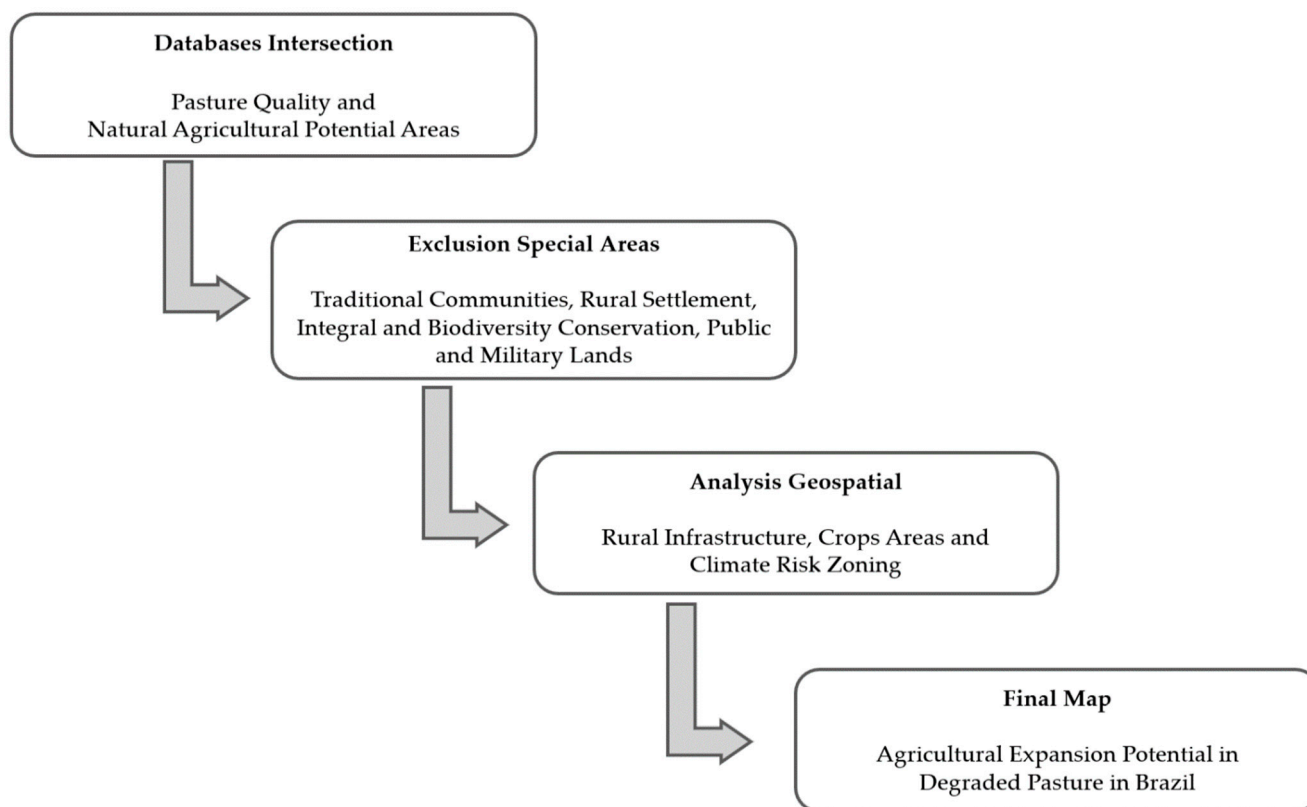


Figure 1. Workflow for the integration of multi-source datasets in a GIS environment used to analyze the potential for agricultural expansion in degraded pasturelands in Brazil.

Table 1. Information the databases used to analyze the potential for agricultural expansion in degraded pasture areas in Brazil.

Layer	Year	Scale	Source	Reference
Pasture quality	2022	1:250,000	Federal University of Goiás (UFG, Universidade Federal de Goiás)	[8]
Land natural agricultural potential	2022	1:250,000	Brazilian Institute of Geography and Statistics (IBGE, Instituto Brasileiro de Geografia e Estatística)	[37]

Table 1. Cont.

Layer	Year	Scale	Source	Reference
Indigenous lands	2021	1:250,000	National Indian Foundation (FUNAI, Fundação Nacional do Índio)	[38]
Afro-Brazilian settlements	2021	1:250,000	National Institute of Colonization and Agrarian Reform (INCRA, Instituto Nacional de Reforma Agrária)	[39]
Rural settlements	2022	1:5000	National Institute of Colonization and Agrarian Reform (INCRA, Instituto Nacional de Reforma Agrária)	[39]
Integral conservation	2019	1:250,000	Ministry of Environment and Climate Change (MMA, Ministério do Meio Ambiente e Mudança do Clima)	[40]
Biodiversity conservation	2021	1:250,000	Ministry of Environment and Climate Change (MMA, Ministério do Meio Ambiente e Mudança do Clima)	[41]
Public lands	2020	1:250,000	Brazilian Forest Service (SFB, Serviço Florestal Brasileiro)	[42]
Military lands	2017	1:250,000	Brazilian Institute of Geography and Statistics (IBGE, Instituto Brasileiro de Geografia e Estatística)	[43]
State and federal highways	2021	1:400,000	National Department of Transportation Infrastructure (DNIT, Departamento Nacional de Infraestrutura de Transportes)	[44]
Rural warehouses	2021	—	National Supply Company (CONAB, Companhia Nacional de Abastecimento)	[45]
Croplands	2022	1:100,000	MapBiomas Project (Brazilian Annual Land Use and Land Cover Mapping Project)	[3]
Climate risk agricultural zoning	2023	1:50,000	Ministry of Agriculture, Livestock, and Supply (MAPA, Ministério da Agricultura, Pecuária e Abastecimento)	[46]

The first step of the analysis consisted of the integration of “Pasture Quality” and “Land Natural Agricultural Potential” base maps (Figure 2). The data related to “Pasture Quality” in Brazil were obtained from the “Atlas of Pasture” produced by the Laboratory of Image Processing and Geoprocessing of the Federal University of Goiás (UFG, Universidade Federal de Goiás) [8,47]. In this Atlas, pastures were classified based on Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) satellite images processed by the non-parametric Random Forest classifier. The input parameters for the RF classification were the 6 multispectral bands (green, red, near infrared, shortwave infrared 1, and shortwave infrared 2); the 5 arithmetic operations (mean, standard deviation, minimum, maximum, and amplitude) involving the multispectral bands; and 3 spectral indices (Normalized Difference Vegetation Index—NDVI; Normalized Difference Water Index—NDWI; and Cellulose Absorption Index—CAI) [48–50], which are sensitive to the chlorophyll, water, and lignin/cellulose contents of the vegetation, respectively.

The study conducted by the UFG used the Moderate Resolution Imaging Spectroradiometer (MOD13Q1) Enhanced Vegetation Index (EVI) time series processed by the Temporal Moving Window Median (TMWM) algorithm to extract stable (i.e., gap-filled series, on a pixel basis) and seasonally adjusted data. From the spatio-temporal analysis of normalized EVI data, it was possible to evaluate different levels of pasture degradation in Brazil, which were classified as Absent ($EVI \geq 0.6$), Intermediate ($0.4 \leq EVI \leq 0.6$), and Severe ($EVI \leq 0.4$). EVI was selected because it has less sensitivity to variations in soil background and atmospheric effects, in comparison with NDVI, another vegetation index available in the MOD13Q1 product [51].

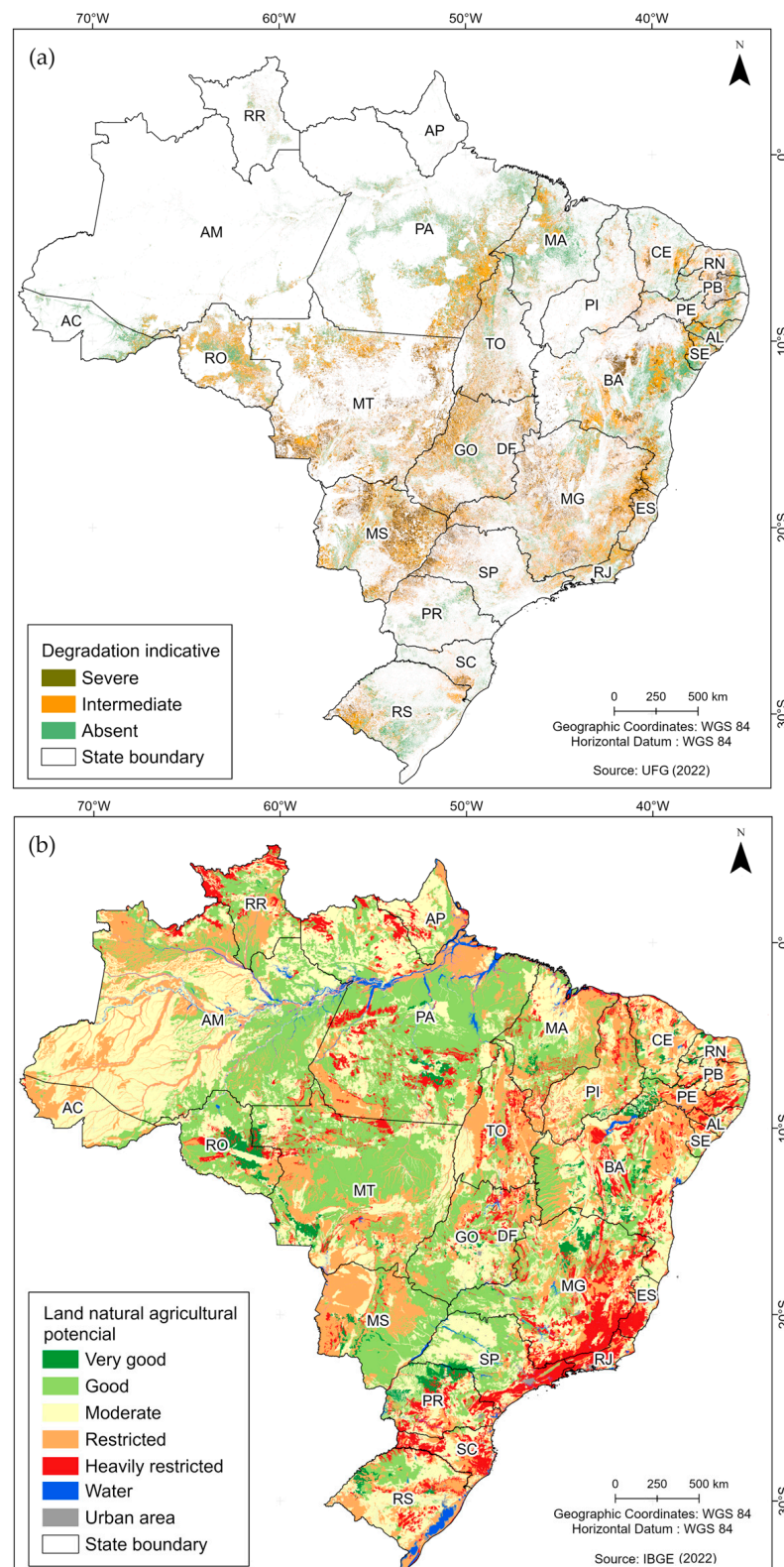


Figure 2. Maps of “Pasture Quality” (a) and “Land Natural Agricultural Potential” (b) in the states in Brazil. AC = Acre; AL = Alagoas; AM = Amazonas; AP = Amapá; BA = Bahia; CE = Ceará; DF = Distrito Federal; ES = Espírito Santo; GO = Goiás; MA = Maranhão; MG = Minas Gerais; MS = Mato Grosso do Sul; MT = Mato Grosso; PA = Pará; PB = Paraíba; PE = Pernambuco; PI = Piauí; PR = Paraná; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RO = Rondônia; RR = Roraima; RS = Rio Grande do Sul; SC = Santa Catarina; SE = Sergipe; SP = São Paulo; and TO = Tocantins.

We also used the map of the “Land Natural Agricultural Potential of Brazil” produced by the Brazilian Institute for Geography and Statistics (IBGE) at 1:250,000 scale [37]. This map identifies five levels of potentials or limitations of Brazilian territory for agricultural expansion, based on soil and topographic characteristics. More specifically, the levels are categorized into A1, A2, B, C, and D classes, depending upon if the lands present have very good, good, moderate, restricted, or strongly restricted potentials for agricultural expansion, respectively (Table 2).

Table 2. Classes of potentials or limitations for agricultural expansion in Brazil based on soil and topographic characteristics.

Category	Potential	Characteristics
A1	Very good	Deep soils, good fertility, good permeability, and location on flat terrains.
A2	Good	Soils located mostly on flat terrains, with some restrictions because of the presence of undesirable/harmful ions and relatively shallow soil depth.
B	Moderate	Soils with moderate restrictions on fertility, presence of expansive clays and undesirable/harmful ions, mostly located on slightly hilly topography.
C	Restricted	Soils with undesirable/harmful ions, presence of expansive clays and with important restrictions regarding shallow soil depth, mostly located in rugged terrains, though they also can occur in flat areas with restrictions due to fluctuations or significant shallow water table (hydromorphism).
D	Strongly restricted	Soils located on terrains with very steep slopes, presence of undesirable soluble salts, and important restrictions regarding their depth; they are mainly devoted to protection, preservation, and conservation of native vegetation.

In the second step of the agricultural expansion analysis, we excluded the following areas labeled “special”: (i) lands belonging to traditional communities, that is, indigenous lands [37] and Afro-Brazilian “quilombola” settlements [38]; (ii) rural settlements for agricultural reform [38]; (iii) permanently protected federal conservation units [39]; (iv) areas with high priority for biodiversity conservation, classified as of extremely high biological importance [40]; (v) undesignated public areas from the National Registry of Public Forests, belonging to federal or state governments and without any destination by the Brazilian Forest Service [41]; and (vi) military areas [42] (Figure 3).

The following datasets were also considered in this study: rural infrastructure associated with state and federal highways [43] and rural warehouses [44]; existing agricultural areas [3]; and data from the Agricultural Climate Risk Zoning for the 2022/23 crop calendar [45] (Figure 4). The Agricultural Climate Risk Zoning is coordinated by MAPA and Embrapa (Brazilian Agricultural Research Corporation, Brasília, Brazil), and considers the risks of adverse climate to identify the best planting dates for rainfed crops based on the local soil water holding capacities, crop coefficients, and precipitation regime. In this study, we considered the medium-textured soils with short-cycle crop varieties as the references. We selected only the municipalities with at least 20 days of the year with a probability greater than 80% to plant and harvest without significant risk of losing production.

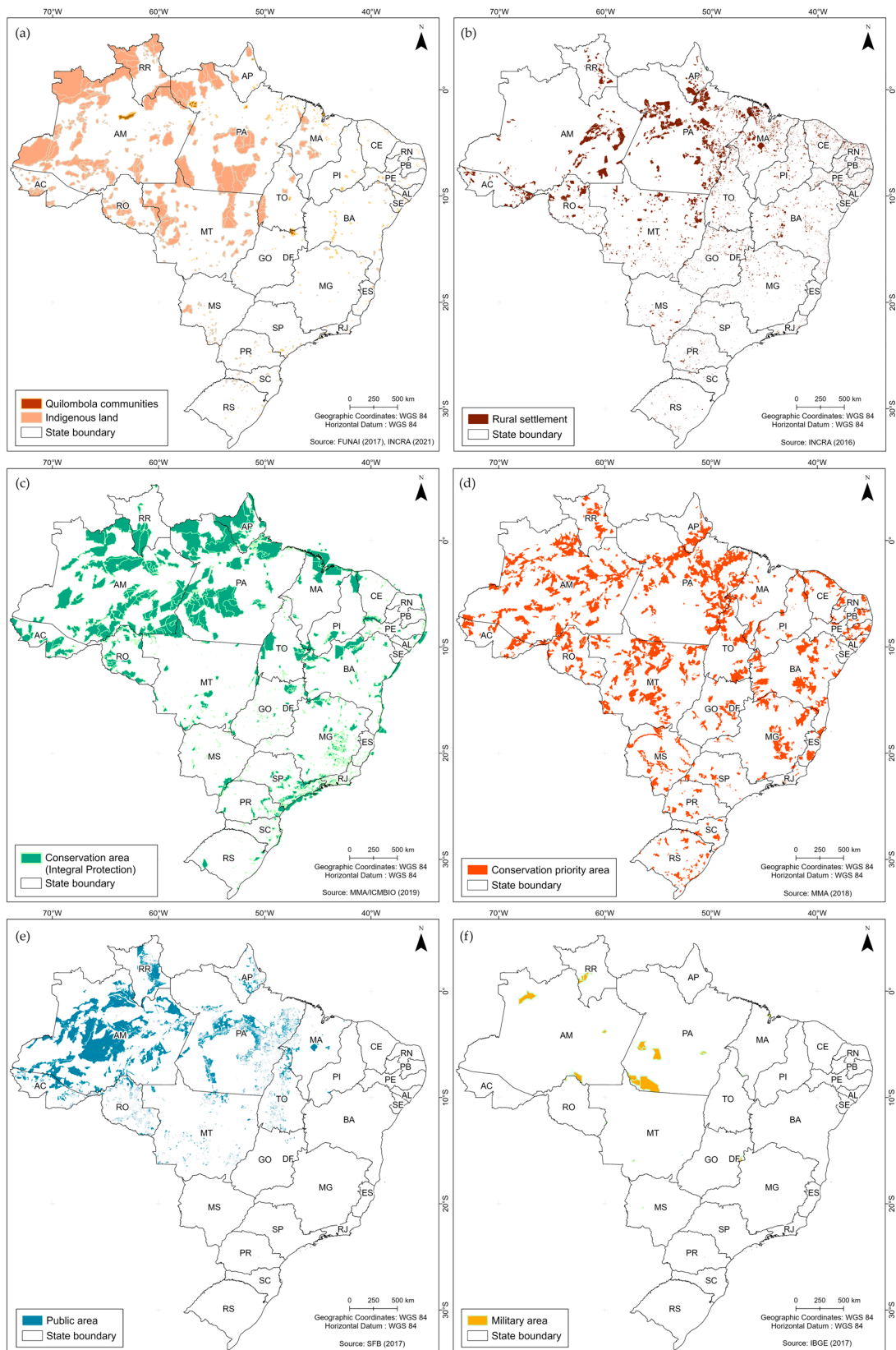


Figure 3. Maps of “Special Areas” in Brazil: Indigenous lands and Afro-Brazilian settlements (quilombolas) (a), rural settlements (b), conservation units (c), priority areas for conservation (d), undesignated public areas (e), and military areas (f).

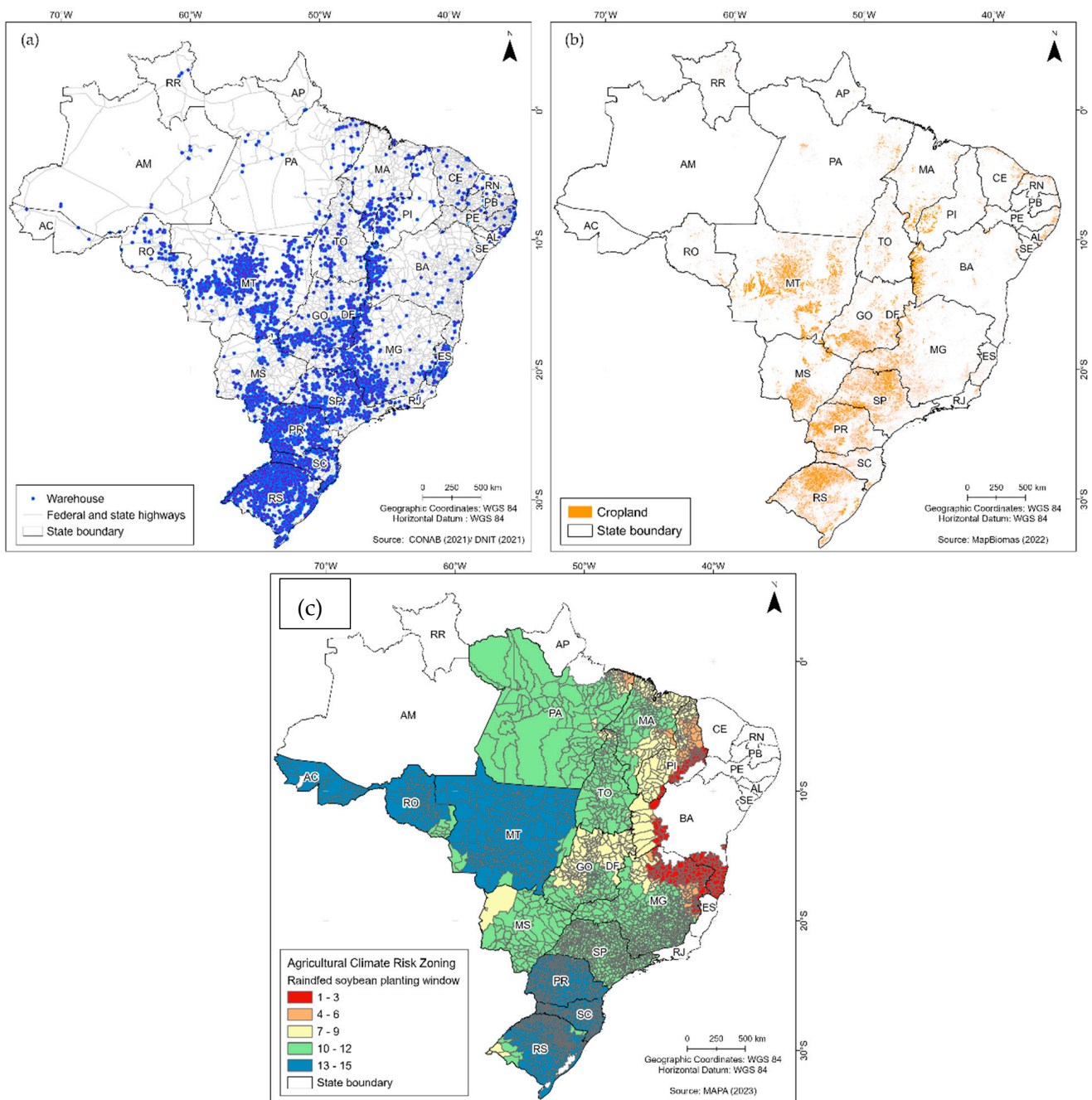


Figure 4. Maps of warehouse and highways (a), croplands (b), and Agricultural Climate Risk Zoning—example of soybeans (c) in Brazil.

3. Results

Table 3 shows the existence of a total of 447.24 million hectares of areas with traditional communities, rural settlements, conservation units, priority areas for biodiversity conservation, undesignated public areas, and military areas, representing about 52% of the national territory. Pastures with moderate or severe limitation on its vegetative vigor [8] covered 109.7 million hectares, which corresponds to 60% of Brazilian pastures.

Table 3. Information processed from the multi-source databases used in the study at the state level of Brazil. Mha = million hectares.

State *	State Area (Mha)	Pasture Quality Area (Degradation)		Natural Agricultural Potential Area **		Special Areas (Mha)	Rural Infrastructure		Crop Area (2022) (Mha)	Number of Rainfed Crops with Low Climate Risk	Agricultural Crop Expansion Potential Area *** (Mha)
		Intermediate (Mha)	Severe (Mha)	Good (Mha)	Very Good (Mha)		Warehouses (Number)	Highways (km)			
AC	16.42	0.30	0.02	1.30	0.01	12.85	14	1611	0.01	26	0.09
AL	2.78	0.58	0.10	0.19	0.07	0.71	73	895	0.34	28	0.04
AM	155.93	0.60	0.14	41.92	0.01	142.39	26	7273	0.01	19	0.11
AP	14.25	0.01	0.01	2.75	0.01	13.21	3	1197	0.02	17	0.01
BA	56.48	7.04	3.61	10.37	2.61	16.34	557	35,479	2.89	39	1.96
CE	14.89	1.51	0.32	1.33	0.68	3.50	84	14,975	0.59	26	0.13
DF	0.58	0.04	0.06	0.31	0.01	0.54	90	1772	0.11	34	0.00
ES	4.61	1.05	0.56	0.04	0.02	1.31	267	7751	0.27	31	0.03
GO	34.02	6.45	3.55	13.57	0.48	5.58	914	26,321	5.45	35	4.68
MA	32.96	2.60	0.57	10.9	0.47	13.47	167	15,067	1.19	30	0.73
MG	58.65	10.66	6.10	13.94	2.11	11.33	1387	43,447	4.84	33	4.01
MS	35.71	6.14	5.72	13.85	0.96	6.88	844	18,878	4.06	35	4.34
MT	90.32	8.92	7.01	41.45	2.05	39.21	2218	26,453	11.78	34	5.12
PA	124.59	6.62	1.33	56.52	1.16	104.64	138	19,091	1.01	28	2.09
PB	5.65	0.68	0.75	0.10	0.20	1.16	32	7400	0.07	28	0.05
PE	9.81	1.38	0.58	0.91	1.03	2.92	45	12,773	0.42	28	0.27
PI	25.18	1.12	0.33	4.41	0.29	5.58	136	4383	1.14	27	0.21
PR	19.93	1.10	0.48	3.69	2.43	3.36	2502	17,902	6.61	32	0.54
RJ	4.38	0.93	0.28	0.01	0.03	1.22	19	2375	0.12	31	0.01
RN	5.28	0.85	0.55	0.44	0.31	1.34	21	1802	0.44	28	0.12
RO	23.78	3.95	0.81	10.14	2.65	15.98	200	5845	0.37	29	1.50
RR	22.36	0.23	0.10	8.16	0.09	20.55	27	1825	0.11	20	0.04
RS	28.17	2.51	0.86	3.85	0.81	3.51	4652	26,353	8.92	34	0.35
SC	9.57	0.57	0.27	0.19	0.01	1.27	994	9579	1.24	32	0.01
SE	2.19	0.54	0.15	0.23	0.06	0.24	3	402	0.11	27	0.04
SP	24.82	2.05	1.67	7.56	0.73	5.17	1053	18,463	7.61	40	0.73
TO	27.74	3.71	1.70	4.10	0.14	12.98	176	15,770	1.32	31	0.79
Total	851.04	72.1	37.6	252.24	19.38	447.24	16,642	345.10	61.04	-	28.02

* AC = Acre; AL = Alagoas; AM = Amazonas; AP = Amapá; BA = Bahia; CE = Ceará; DF = Distrito Federal; ES = Espírito Santo; GO = Goiás; MA = Maranhão; MG = Minas Gerais; MS = Mato Grosso do Sul; MT = Mato Grosso; PA = Pará; PB = Paraíba; PE = Pernambuco; PI = Piauí; PR = Paraná; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RO = Rondônia; RR = Roraima; RS = Rio Grande do Sul; SC = Santa Catarina; SE = Sergipe; SP = São Paulo; and TO = Tocantins. ** Natural agricultural potential area means the total land suitable for crop production based on favorable conditions in terms of soil, topography, and precipitation. Special areas means areas fully protected by law (e.g., conservation units, indigenous areas, and military areas). *** Agricultural crop expansion potential area means degraded pasturelands with high potential for rainfed crop plantation.

Approximately 28 million hectares of planted pastures with signs of severe and intermediate degradation occur in areas with very good and good natural agricultural potential, excluding areas with high biodiversity conservation priority and special areas (Figure 5). Approximately 11 million hectares of pastures with “Severe” degradation are in areas with “Good” or “Very Good” agricultural potential while 18 million hectares of pastures with “Intermediate” degradation level are in areas with “Good” or “Very Good” agricultural potential. This represents a potential expansion of approximately 30% of the current grain production area in previously converted lands. At the state level, the largest quantities are found in the states of Mato Grosso (5.1 million ha), Goiás (4.7 million ha), Mato Grosso do Sul (4.3 million ha), Minas Gerais (4.0 million ha), and Pará (2.1 million ha) (Figure 6). In relation to the planted area in the 2022/2023 crop calendar [45], states such as Minas Gerais,

Mato Grosso do Sul, Goiás, Bahia, and Mato Grosso presented a potential of agricultural expansion in areas of degraded pastures of approximately 92%, 69%, 66%, 52%, and 24%, respectively. An importance aspect is that degraded pastures are concentrated in specific regions in Brazil, facilitating the planning of public and private resources to promote lands recovery [20].

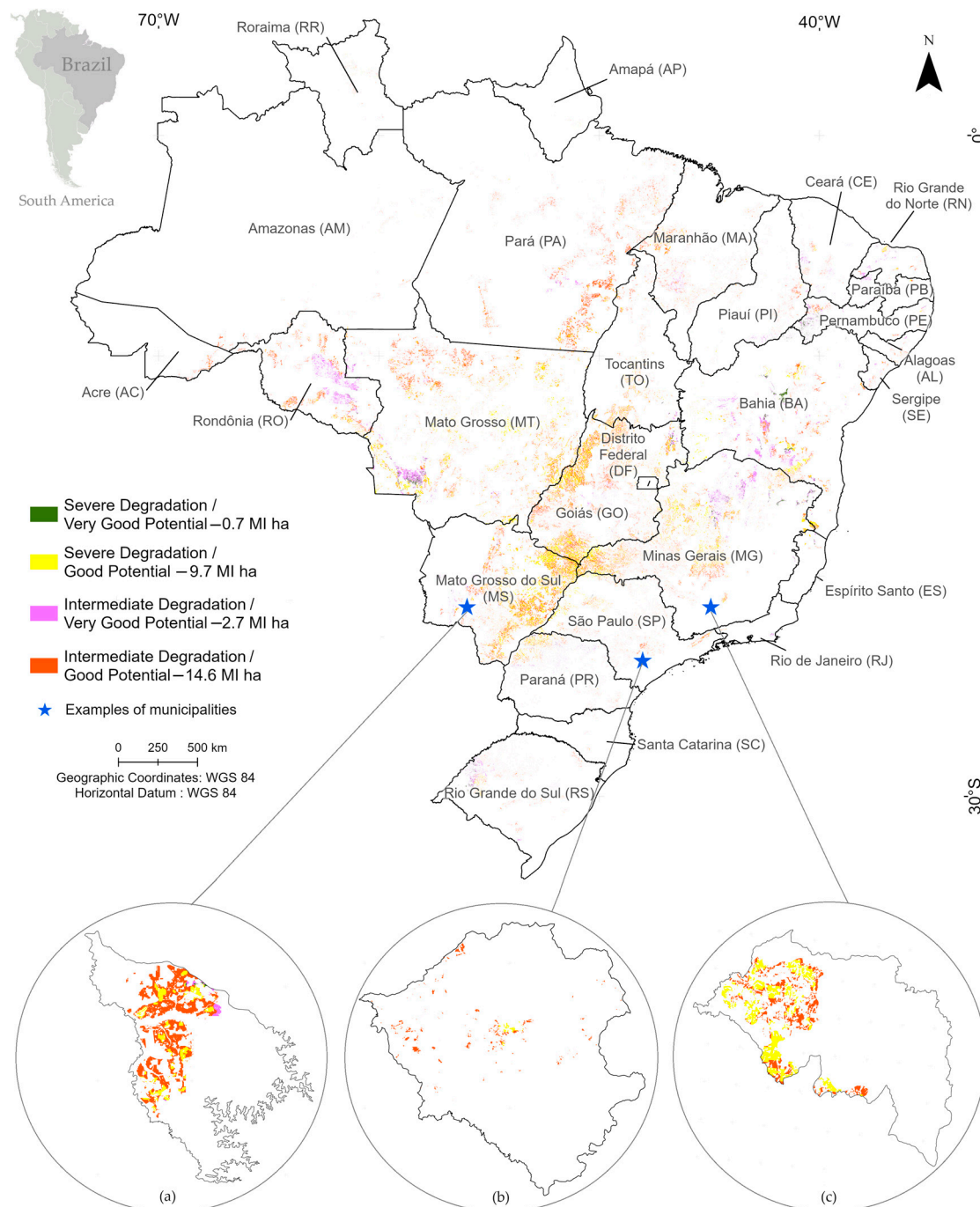


Figure 5. Spatial distribution of potential agricultural expansion areas by state, considering the presence of planted pastures, with indicators of severe and intermediate degradation in areas with very good and good natural agricultural potential in Brazil and municipalities. Examples: (a) Guia Lopes da Laguna—MS, (b) São Miguel Arcanjo—SP and (c) Ingai—MG.

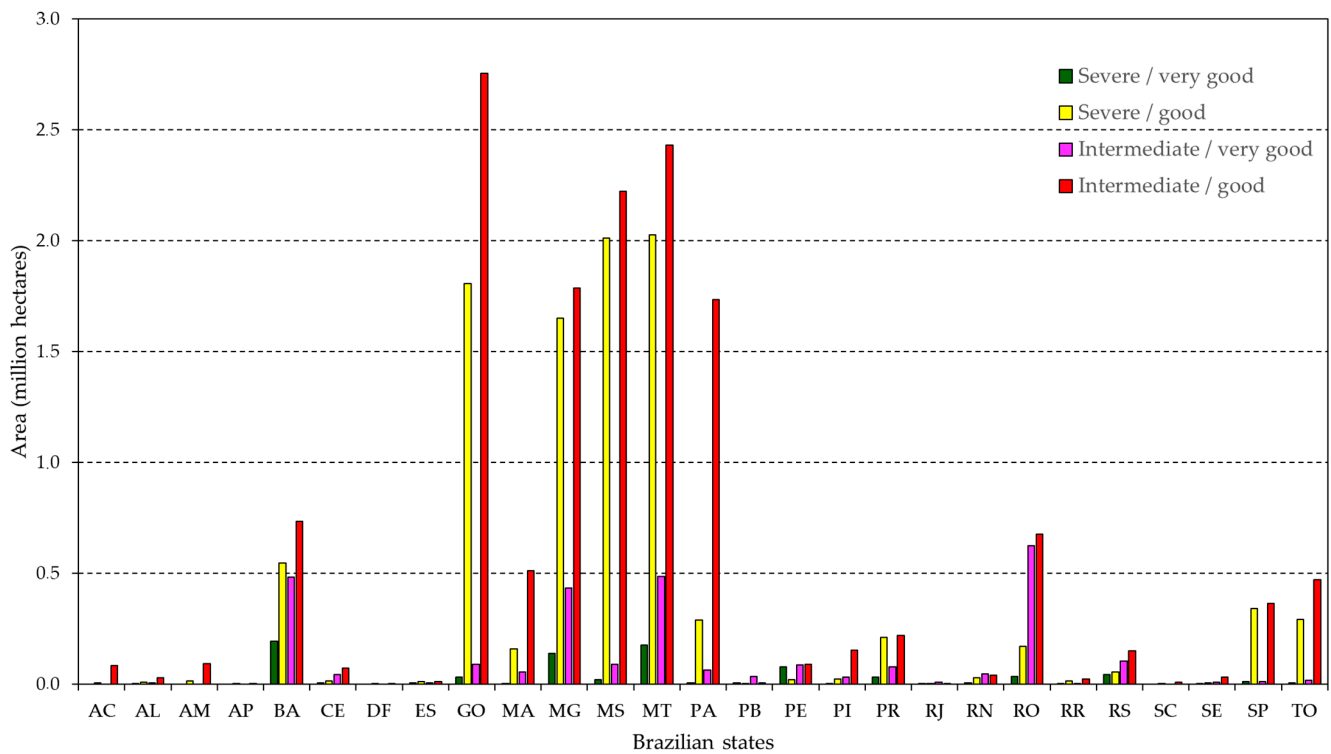


Figure 6. Estimates of agricultural expansion possibilities for each Brazilian state, considering the presence of planted pastures, with indicators of severe pasture degradation and very good agricultural potential, severe pasture degradation and good agricultural potential, intermediate pasture degradation and very good agricultural potential, and intermediate pasture degradation and good agricultural potential. AC = Acre; AL = Alagoas; AM = Amazonas; AP = Amapá; BA = Bahia; CE = Ceará; DF = Distrito Federal; ES = Espírito Santo; GO = Goiás; MA = Maranhão; MG = Minas Gerais; MS = Mato Grosso do Sul; MT = Mato Grosso; PA = Pará; PB = Paraíba; PE = Pernambuco; PI = Piauí; PR = Paraná; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RO = Rondônia; RR = Roraima; RS = Rio Grande do Sul; SC = Santa Catarina; SE = Sergipe; SP = São Paulo; and TO = Tocantins.

Considering the lack or deficiency of rural infrastructure for rural development, Table 4 shows the data regarding the distance of potential areas for agricultural expansion in relation to rural highways and warehouses.

Table 4. Spatial distribution of current agricultural and pasture areas (millions of hectares) in relation to the existing infrastructure of warehouses and state and federal highways in Brazil.

Land Use	Infrastructure		Distance from Highways						Total
			20 km	40 km	60 km	80 km	100 km	>100 km	
Agriculture	Warehouses	Area	51.14	7.22	1.72	0.56	0.23	0.15	61.03
		%	83.80	11.83	2.83	0.92	0.38	0.25	100.00
	Highways	Area	57.10	3.34	0.48	0.11	0.00	0.00	61.03
		%	93.56	5.47	0.79	0.18	0.00	0.00	100.00
Pasture	Warehouses	Area	54.00	48.61	31.98	18.06	10.31	12.66	177.64
		%	30.40	27.36	18.00	10.17	5.80	7.13	100.00
	Highways	Area	158.63	14.95	2.84	0.77	0.35	0.10	177.64
		%	89.30	8.42	1.60	0.43	0.20	0.06	100.00

4. Discussion

Our study was based on the following aspects: (i) cultivated pastures in Brazil are spread throughout the country, are slightly sensitive to the natural conditions of soil,

climate, and topography, and are highly sensitive to degradation because of poor management and/or low chemical fertilization; (ii) some of the degraded pastures are located in areas suitable for rainfed crop production, with favorable soil, climate, and topographic conditions; (iii) currently, there are validated technologies, especially the crop–livestock integration system, that allow crop production in some degraded pastures; (iv) areas with degraded pastures that are suitable for crop production can be identified by integrating additional multisource data, mainly those related with soil, climate, topography, and infrastructure. Data integration of different publicly available layers of information in a GIS environment allowed us to map the severely and moderately degraded pastures that are suitable for crop production.

According to the 2017 Agricultural Census [52], rural producers declared the existence of a total of 12 million hectares of pastures to be in “poor condition” in Brazil. Different methodologies based on remote sensing data have indicated higher levels of degraded areas. For example, Andrade et al. [53] presented a study based on time series analysis of NDVI derived from SPOT Vegetation satellite images, indicating that 173 municipalities in the Cerrado biome (about 25% of the Brazilian territory) had more than 50% of their cultivated pastures with some degradation process, totaling about 32 million hectares. As already reported in the Introduction section, pasture degradation can be analyzed from the agronomic and biological points of view [18]. Regardless of the process, both result in a series of environmental impacts, such as increased soil erosion, soil compaction, and greenhouse gases emission. In addition, the intensive land use also affects the quality of the water resources [54].

Pasture degradation occurs in practically all regions of Brazil, causing economic and environmental losses. There is no typical vegetation formation in which degradation is more severe or less severe, since degradation is primarily a consequence of inadequate pasture management by farmers. In other words, pasture degradation in Brazil can be found in regions dominated by dense or open ombrophilous forests, mosaics of grasslands, shrublands, and forestlands in different proportions, and grass-dominated vegetation with or without the influence of periodic inundation [55]. Degraded pastures can be found in regions with an average annual precipitation ranging from approximately 300 mm to 2000 mm, and on quite diverse soil types, especially Ferralsols, Cambisols, Acrisols, Gleysols, Arenosols, and Plinthosols, among others, depending on the region.

Data on the land natural agricultural potential in Brazil [37] indicate that approximately 271 million hectares are classified as “good” and “very good” for agricultural development, representing around 32% of the national territory. The 61 million hectares of planted pasturelands that were mapped by the MapBiomass Project [3] indicate that 95% of these areas are within 40 km of warehouses and 99% within 40 km of major highways (Table 4), or 54% of the pastures are within 20 km of warehouses and 89% within 20 km of highways. These results indicate a high potential for possible agricultural expansion in pasturelands, when analyzed in terms of access to existing infrastructure.

According to the recommendations of ZARC, there are several annual crops that can be used to replace (or integrate with) cultivated pastures with signs of degradation. The number of potential annual crops varies from 17 to 40 depending on the state, and include peanuts, rice, oats, cotton, canola, sugarcane, barley, corn, millet, beans, chickpeas, sesame, sunflower, castor bean, soybeans, sorghum, wheat, and triticale, among others. The choice of crop is site-specific in terms of property profile, planting date, soil type, and crop variety. Perennial crops can also be an option for replacing low quality pastures, such as coffee, pineapple, plum, banana, cocoa, cashew, citrus, coconut, palm oil, guava, apple, papaya, cassava, passion fruit, watermelon, nectarine, pear, peach, forage palm, pepper, pupunha, sisal, and grape.

Guia Lopes da Laguna (Mato Grosso do Sul State), São Miguel Arcanjo (São Paulo State), and Ingaí (Minas Gerais State), with 17,403, 790, and 2853 hectares of pastures with some level of degradation, respectively, are good examples of municipality in the areas of potential agricultural expansion over degraded pastures (Figure 5a–c). In these municipi-

palities, participating in the Center of Science for Development in Digital Agriculture [56], which aims to connect farmers to innovations that cut costs and assure agricultural sustainability, the ZARC indicates the annual crops such as beans, rice, sorghum, sunflower, cotton, corn, soybeans, oats, wheat, corn/pasture integrated system, and some perennial crops.

Some regional studies have been conducted to better understand the process of pasture degradation and agricultural dynamics, based on geospatial analyses, especially over the Cerrado biome. Victoria et al. [34,35] evaluated the climatic and topographic characteristics of areas occupied by annual crops, and identified planted pastures with similar conditions. They indicated that most pastures with potential for expansion of new annual agriculture areas are found in the Goiás State (11.6 million ha), followed by Mato Grosso do Sul (10.0 million ha), Minas Gerais (7.9 million ha), and Mato Grosso (6.8 million ha). Agrosatélite [57] analyzed the soybean expansion in the Cerrado biome between 2000 and 2021 using remote sensing technologies and geospatial database analysis, reporting an area expansion of approximately 300%, from 7.43 million hectares to 21.43 million hectares.

Regardless of the differences in the methodological approach, the above-mentioned studies pointed out the existence of considerable extension of lands suitable for agriculture that are currently occupied by pastures with some level of degradation. This finding shows the relevance of using all available information, the synergy of observations from different sensors, and the integration of spatial data with historical statistical data that are produced through census or questionnaire-based surveys [58]. Land degradation and climate change pose enormous risks to global food security.

In beef production, it is essential to analyze new approaches and metrics for animal productivity in pastures, since production and sustainability require rigorous science-based evidence to inform private decisions and public policies [59]. The forward-looking, resilient agriculture requires the incorporation of degraded lands, identification of key vulnerabilities, improved knowledge exchange to support strategies of producers, and policy options that provide multiple “wins” for land, climate, and biodiversity [60]. Data organization, integration, and analysis are becoming increasingly relevant to generate more detailed, qualified, and accurate information for more sustainable rural development plans.

5. Conclusions

In this study, we concluded that there are around 28 million hectares of planted pastures in Brazil that are in the process of degradation with the natural potential for the establishment of agricultural crops. The use of these areas in the process of degradation would increase the area planted with annual crops in the country by around 35% in relation to the 2022/2023 crop calendar.

The data generated in this study allowed us to better portray the country’s agricultural dynamics and the agronomic and environmental characteristics of current pasture lands with different levels of degradation. This can provide better support for decision-making proposals regarding regional public policies and rural extension. The possible replacement of degraded pasture areas by agricultural crops must occur in line with Brazilian environmental legislation, techniques, and practices that favor the increase of their productivity, and consequently reduce the pressure to suppress natural vegetation.

Among the drawbacks of the study, we can highlight the limited or even unavailability of some crucial geospatial data related to pasture degradation in Brazil that, to some extent, made our analysis limited. Among them, we can point out the lack of historical data on the pasture degradation in Brazil, the lack of information about the pasture management by farmers, and consistent soil physical, chemical, and biological lab analyses over pasturelands for validation purposes.

In similar analyses in the future, field validation activities, regional databases, and social and economic information from areas with the greatest potential for agricultural expansion and pastures with different levels of biomass production should be considered. Although quite challenging, there is also room to improve the pasture degradation map by using different thresholds of spectral indices for different ecoregions of Brazil. The

idea here is to consider the different carrying capacities of pastures, which are strongly dependent on soil and climate, and the relative importance of the type of degradation, either agronomic (productivity) or biological (sustainability) degradation, which is also region-dependent.

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