Review

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From Traditionally Extensive to Sustainably Intensive: A Review on the Path to a Sustainable and Inclusive Beef Farming in Brazil

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From Traditionally Extensive to Sustainably Intensive: A Review on the Path to a Sustainable and Inclusive Beef Farming in Brazil

Mariana A. Pereira [1,*], Davi J. Bungenstab [1], Valeria P. B. Euclides [1], Guilherme C. Malafaia [1], Paulo H. N. Biscola [1], Gilberto R. O. Menezes [1], Urbano G. P. Abreu [2], Valdemir A. Laura [1], Ériklis Nogueira [1], Rodiney de A. Mauro [1], Marta P. da Silva [1], Alessandra C. Nicacio [1], Roberto G. de Almeida [1], Rodrigo da C. Gomes [1], Juliana C. B. Silva [1] and Vanessa F. de Souza [1]

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Simple Summary: Agriculture worldwide has been challenged on how to grow sustainably to feed a rising population without depleting natural resources. This is also the case in Brazil and, in particular, for beef farming, which is carried out across the country in all biomes. This article reviews the major changes in beef farming over the last few decades, and draws attention to how these changes have been shifting production systems toward a sustainable intensification of grass-fed beef. We also discuss about the potential impact of technological developments on small to medium scale farms and reflect on some initiatives that may help farmers to keep up to date with climate-friendly technologies. Their persistence will rely on their ability to remain competitive, which requires the incorporation of sustainable technologies, development of new capabilities such as digital literacy, and access to credit and technical assistance. This study has implications for policymakers, financial institutions and extension services.

Abstract: Brazil became a major player in the global beef market, after the market liberalization in the 1990's, and experiencing a substantial development. Nonetheless, the environmental impact of beef production associated with land use and greenhouse gas emissions has been under discussion. The necessity of increased adoption of sustainable technologies, however, may preclude some farmers to keep up to date with technological advances. This article describes the major historical changes in beef farming and how they have been shifting production systems toward a sustainable intensification of grass-fed beef, with likely impacts for farmers. We combined an extensive literature review, public data and our own insights, as senior researchers, to achieve that. The trajectory shown here evidenced the substantial technological development underway in Brazilian beef farming, with strong support of public policies for decarbonizing agriculture. Nonetheless, the pace of this sustainable transition may affect small to medium farmers unable to cope. Our recommendations, therefore, involve a broad program of technical assistance and training on sustainable technologies and other supportive practices, including financial and digital literacy. Additionally, we suggest an alternative credit system, with progressive borrowing allowances to ensure financial resources to support a sustainable and inclusive transition of Brazilian beef farming.

Keywords: beef farming; Brazil; sustainable intensification; public policies

1. Introduction

Brazil stands out in the global beef market, holding the world's largest commercial herd and leading beef exports (FAO, 2023) [1]. The Brazilian beef supply chain saw vigorous growth over the past decade. The sector's GDP increased from BRL[1] 356 billion in 2011 to BRL 913 billion in 2021, with an average growth rate of 9.9% (ABIEC, 2023) [2]. According to Basso et al. (2024) [3], in 2023, crops, livestock, and the agribusiness as a whole contributed appoximately 18%, 6.8%, and 24.8% to Brazil's GDP, respectively. The number of importing countries grew, with China becoming a significant destination alongside other established markets like Hong Kong, the European Union, Egypt and Chile. The new sanitary status of bbeng free from foot-and-mouth disease without vaccination, achieved by several Brazilian states, has opened new international markets (Menezes et al., 2020) [4]. Domestically, livestock productivity increased by 159%, from 1990 to 2020, while pasture area decreased by 13% (Malafaia et al., 2021) [5], now estimated at 153.8 million hectares (Table 1).

Table 1. Brazil's beef sector in 2022.

Categories	2022
Area (million hectares)	153.8
Herd (1,000 head)	202.8
Meat Production (1,000 t CWE)	10.8
Import (1,000 t CWE)	80.6
Export (1,000 t CWE)	3.0
Internal Availability (million t CWE)	7.8
Population (millions of inhabitants)	214.1
Availability Per Capita (kg/person/year)	36.7

Source: ABIEC Beef Report 2023 [2].

Since the 1990s, after market liberalization by the Brazilian Government, the beef supply chain underwent technological modernization, resulting in higher productivity, better meat quality, and greater competitiveness. From 2000 to 2010, slaughter age was reduced to 33 months, heifers' age at first breeding dropped from 36 to 30 months, weaning rates increased from 57% to 68%, and weaning weight from 167 to 190 kg (McManus et al., 2016) [6]. Favorable climatic conditions, abundant land at relatively low prices, large labor supply, and the development of tropically-adapted technologies significantly contributed to the sector's boom (Malafaia et al., 2021) [5], suppoted by public policies (Chaddad, 2015) [7], alleviating previous concerns over beef imports, common until the 1980s.

However, growth in the sector has not been uniform across regions and types of farmers, and remains a significant challenge in reducing inequalities and preventing social displacement. Moreover, modern beef farming must rapidly address environmental issues, such as its link to deforestation and the cattle carbon footprint, both crucial for combating global warming. Considering the crucial role Brazilian beef plays in global food security and its influence on worldwide beef markets (FAO, 2023) [1], understanding the evolution of the country's sector and the main challenges ahead will better inform policymakers, researchers, and other stakeholders involved in supporting and promoting sustainable farming practices, both domestically and internationally.

This article aims to describe the major changes in Brazilian beef farming in the recent past and reflect on the issues and challenges ahead from a multidisciplinary perspective. For this purpose, we used a mixed approach, combining an extensive literature review, based on scientific research and public data to enrich our exploration and insights.

[1] 1.00 BRL = 0.1926 USD = 0.1818 EUR

2. Historical Development of Beef Farming in Brazil

2.1. The Transformation of Cerrado and Expansion to the North

Until the 1960s, cattle herds were predominantly found in the South and Southeastern areas of Brazil, under extensive, low-input systems. In the late 1960s, public policies encouraged farmers to "conquer" the *Cerrado*, a savanna-type vegetation typically found in Central Brazil. Agriculture began moving northwards, clearing land for cash crops like dryland rice and soybeans. With the advance of crops, machinery became available for sowing pastures. Palisade grasses from Africa were introduced in the early 1970s, along with Indian cattle (Zebu breeds), creating a favorable environment for cattle farming (Chaddad, 2015) [7]. The Brazilian Agricultural Research Corporation – EMBRAPA, created in 1973, was strategic for developing tropical technologies adapted to Cerrado's harsh conditions, which was later considered the Sustainable Tropical Agriculture Revolution of the 20th century (Basso, Neves and Grossi-de-Sá, 2024) [3].

Cash crops expanded further northwards, followed closely by cattle herds. Soybeans and maize, in particular, but also sugarcane and eucalyptus forestry became increasingly economically attractive in Central Brazil, especially in fertile soils, constantly pushing cattle farming to fringe areas. Consequently, traditional cattle farming regions, such as Southern and Southeastern Brazil, gradually saw a reduction in herd size and growth rates (McManus et al., 2016) [6], while growth has remained robust in Northern Brazil. Our own analysis confirms this trend, showing a significant shift of herds from the central to the northern region of Brazil over the last 30 years (Figure 1).

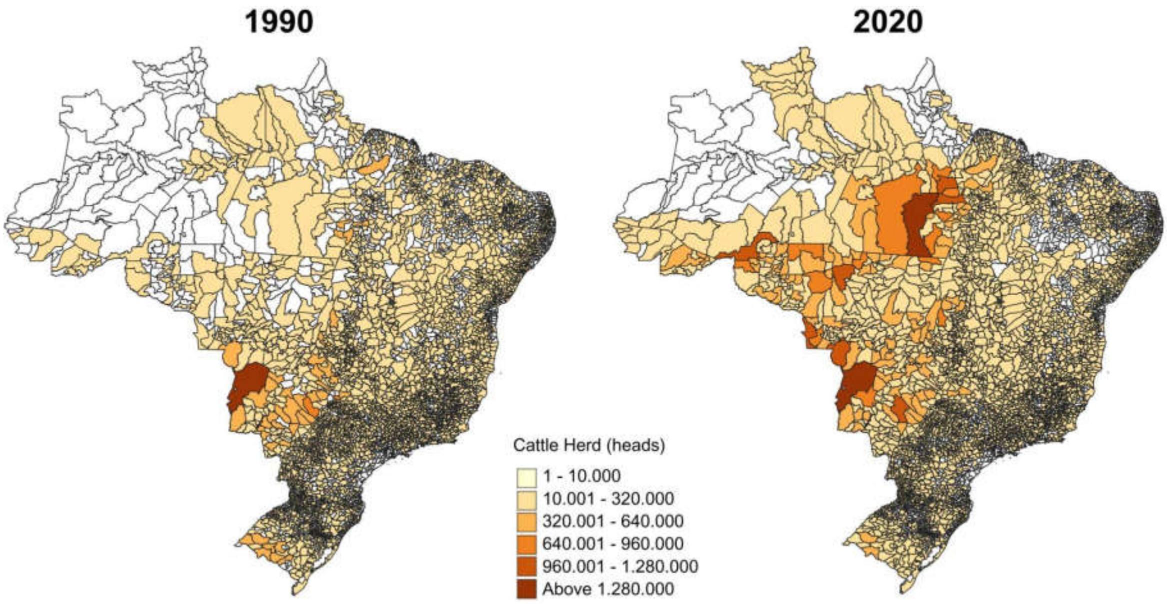

Figure 1. Distribution of cattle herd in Brazil, in 1990 and 2020. Source: Prepared by the authors. Adapted from the Brazilian Institute of Geography and Statistics - IBGE.

This shift can be attributed not only to lower land prices in the north and overall improvements in farming techniques, adapted to the Amazonian biome (Mores et al., 2022) [8], but fundamentally to a significant increase in the regional demand for cattle products, like milk and beef, due to population and purchasing power growth, as Faminow (1996) [9] highlighted. According to official data, the region's population surpassed 17 million inhabitants in 2022, with Pará, Amazonas, and Rondônia leading the ranking (IBGE, 2022) [10]. Pará, Roraima and Acre are the major suppliers of the regional beef market (McManus et al., 2016) [6]. More recently, cattle herds have been expanding into the states of Maranhão, Tocantins, Piauí, and Bahia, comprising the so-called "Matopiba". This new agricultural frontier plays an important role in shifting the axis of current Brazilian agricultural production and will continue to do so in the coming decades (Mores et al., 2022) [8].

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Despite ongoing changes, Central Brazil remains a signicant cattle zone, with Mato Grosso do Sul, Goiás, and Mato Grosso states being particularly relevant (McManus et al., 2016) [6], as illustrated in the map above (Figure 1, year 2020). According to ABIEC (2023) [2], in 2021, the North and Central regions held 20.2% and 35.4% of the cattle herd, respectively.

2.2. The Launch of Improved Tropical Forage and New Husbandry Practices

Grasslands are the primary land use in Brazil (21%), after land spared for conservation and indigenous peoples (40.7%) and for conservation within private farms (25.6%) (Table 2). Brazilian beef is essentially grass-fed on extensive sown pasture systems. About 16% of the cattle slaughtered is finished on feedlots (ABIEC, 2023) [2], usually only in the last three to four months prior to slaughter. While not the standard, these feedlots can be strategic for improving production and reducing externalities, as they can save a year of extra grazing and help to reduce greenhouse gas (GHG) emissions by lowering the age at slaughter and, therefore, the total emissions per head.

Table 2. Areas allocated to preservation of native vegetation and other land uses in Brazil (2018).

CATEGORY OF LAND USE		AREA (ha)	% OF BRAZILIAN AREA (2018)
Native Vegetation Preserved on Rural Areas		218,245,801	25.6
Full Conservation Units		88,429,181	10.4
Indigenous Peoples Reserves		117,338,721	13.8
Native Vegetation on Unclaimed or Unregistered Areas		139,722,327	16.5
Native Pastures		68,022,447	8.0
Sown Pastures		112,237,038	13.2
Crops		66,321,886	7.8
Commercial Forestry		10,203,367	1.2
Infrastructure, Cities And Others		29,759,821	3.5
	TOTAL	**850,280,588**	**100**

Source: Adapted from Carvalho 2019 [11].(Free translation).

Ninety percent of milk and beef production in Brazil is exclusively pasture-based (ABIEC, 2019) [12], as the climate and land extension favor this strategy, resulting in one of the lowest beef costs in the world (Deblitz, 2023) [13]. Pastures, therefore, play a strategic role in Brazilian beef competitiveness while also allowing for the use of least-prone agricultural land. The introduction of *Brachiaria* grass, back in the 1970s, well adapted to Brazilian climate and soil, was one of the milestones in the development of livestock farming in the country.

Until 1985, natural grasslands were predominant along with low-input farming systems. About ten years later, they represented only 30% of total Brazilian pastures, mainly due to physical characteristics and cultural traditions (check Box 1). From the 1980s onwards, the collection of forage genetic resources in Brazil and Africa, and the selection process, based on their natural variability or through crossings, set the grounds for the Brazilian tropical forage development program, at Embrapa[2], which led to a substantial increase in animal production in the following decades (Valle et al., 2009) [14]. Several forage cultivars have been launched and adopted in the most diverse production systems and biomes, including those of the genera: *Brachiaria*, *Panicum*, *Andropogon*, *Stylosanthes*, *Arachis* and *Cajanus*.

Another milestone for beef farming was the introduction of Indian cattle, mainly Nellore, Guzera and Gyr breeds. Nellore (*Bos indicus*) and its crosses became the main beef breed (Miszura et al., 2021) [15], representing about 80% of the Brazilian herd. Nellore is extremely well-adapted to the country's conditions (Baruselli et al., 2004; Lima et al., 2023) [16,17], notably for heat and parasite tolerance, while maintaining the capacity to efficiently use low-nutrition tropical forages. Genetic programs

[2] Embrapa leads the National System of Agricultural Research and is publicly funded by the Federal Government.

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which started in the 1980s improved this performance through progressively shifting from empirical animal selection to fix racial characteristics to production efficiency (Euclides Filho, 2009) [18]. As computational resources evolved, so did the genetic evaluation, with the pioneering initiative of Embrap working with sire models, at first, and then animal models. Nowadays, Embrapa-Geneplus Beef Breeding Program, Zebu Genetic Improvement Program (from Brazilian Zebu Breeders Association - ABCZ) and other breeding programs are increasingly incorporating genomic data and innovative selection criteria associated with carcass quality, sexual precocity, feed efficiency, and environmental impact (e.g., water intake, greenhouse gas emissions).

Nellore heifers, however, are late in their development and onset of puberty, with their first parturition occurring, on average, around 36 months, in contrast with 24 months by European breeds (*Bos taurus*) (MISZURA et al., 2021) [15]. The earlier the reproductive life starts, the greater is the females' productivity (de LIMA et al., 2020; TERAKADO et al., 2015) [19,20], which is determinant for profitability in cow-calf operations, along with the birth rates. In this context, reproductive bio-techniques have been of particular importance for promoting sound reproduction management, given the prevalence of extensive farming systems in Brazil. Artificial insemination at detected estrus (AIE) and timed artificial insemination (TAI) are the primary tools used to increase production through introducing superior sires in commercial herds, including fertility-related ones. According to Asbia (2022) [21], 23.5% of the 63 million beef cows are currently inseminated in Brazil, mostly with Zebu breeds. By large, TAI is the main method (98% of cases) and results in a 50% pregnancy rate, on average in each shoot (Nogueira et al., 2019) [22]. The annual sales growth rate of synchronization protocols for TAI has been around 32%, in contrast with 6.7% for semen doses.

Other reproductive bio-techniques still face scaling challenges in Brazil. *In vitro* embryo production (IVP) for embryo transfer (ET), sex-sorted semen, vitrification or freezing for direct transfer remain a niche market, mostly used in superior genetics herds. According to BARUSELLI et al. (2019) [23], the challenges to increase the adoption of these biotechnologies include: lack of comprehensive understanding of productivity and economic benefits from using such technologies; insufficient number of specialists on the field; relatively low efficiency of AI and ET programs; research failing to assess reproduction within a systems approach; inadequate coordination of the supply chain compromising the communication and transfer of these technologies to farmers, among others. Bezerra et al. (2019) [24] argue that these technologies are promising and eventually will reach commercial herds. Brazil is one of the largest producers of *in vitro*-derived cattle embryos and is the leader of IVP embryos transfers of the world, holding a market share of 37%. The country has a high number of dedicated laboratories and a vast herd of *B. indicus* cows, which are known for higher oocyte recovery, number of viable oocytes, and production of viable embryos than the *B. taurus* cows (Pontes et al., 2010; Sales et al., 2015) [25,26].

Alongside the genetic improvement of cattle breeds, the progress of the nutrition industry has occurred, focusing primarily on the nutrition gap between nutrient poor soils and forage, and the increasing nutrient demand by genetically improved cattle. In the 1970s, mineral deficiencies in Brazilian soils were identified as one of the major reasons for mineral undernutrition-related diseases, commonly found in cattle (Sousa & Dirsie, 1985, Sousa et al., 1989, Tokarnia et al., 2000) [27–29]. In the following decades, a consistent nutrition industry emerged across the country, promoting adequate mineral nutrition by developing and commercializing mineral mixtures that helped to tackle cattle deficiencies mainly of phosphorus, sodium, copper and zinc. It allowed for significant improvements in growth rate, carcass quality, fertility and health. Furthermore, a number of new nutritional strategies based on protein, energy and feed additives supplementation (Araújo et al., 2017) [30] were developed and adopted, minimizing the performance loss in the dry season and, occasionally, improving it in the rainy season. With the expansion of Brazilian agriculture and the structuring of grain processing industry, larger amounts of cereals and co-products became available in the market (Silvestre & Millen, 2021) [31], which favored the growth of feedlot operations that, today, finish about 7.6 million cattle (ABIEC, 2023) [2]. Estimates of another 5 million head are also finished with high grain diets (e.g., 1.5% to 2% intake of the body weight in concentrates) while still

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grazing[3]. As intensive and semi-intensive finishing systems are becoming more widely adopted, the carcass weight is increasing (ABIEC, 2023) [2] and the age at slaughter is decreasing.

Such outstanding development of the Brazilian beef sector was only possible with the support from Public Policies, farmers' private investments and better coordination of the supply chain. Between 1950s and 1990s, several public policies encouraged the occupation of Central Brazil through agriculture (Barbosa, Duarte and Staduto, 2021) [32]. The farms' profitability relied more on asset valuation due to inflation and herd/land expansion than on productivity (Stabile et al., 2023) [33]. More recently, policies shifted to shape the future of Brazilian farming towards a sustainable intensification of the production systems. We present the two most influential policies below.

2.3. Key Public Policies for Recent Developments of the Brazilian Agriculture

2.3.1. The Forest Code

The Brazilian Forest Code was established in 1934, revised in 1965, and reformulated in 2012. The so-called "Brazil New Forest Code" sets boundaries for the use and protection of private land in Brazil (Chiavari, Lopes and Machado, 2023) [34]. The Code mandates that farms set aside areas for preservation and protection as Permanent Protected Areas (PPAs) or Legal Reserves (LR). PPAs are critical environmental areas that must remain intact , whereas LRs are areas covered by native vegetation that can be sustainably managed but not cleared. The size of PPA varies based on geographical features and physical attributes (e.g. size of water bodies; slope steepness), while the size of LR ranges from 20% to 80%, depending on the biome and type of vegetation. In the Legal Amazon, farms must maintain 80% as LR, if in typical forest areas, 35% if in Cerrado areas (savannah type) and 20% if in grasslands areas; outside the Legal Amazon, 20% must be maintained as LR, irrespective of the type of vegetation (for more information on Legal Amazon, check Chiavari, Lopes and Machado, 2023) [34]. PPAs and LRs are not exchangeable and, where both exist, PPA areas must be added to the LR. As shown in Table 2, nearly 200 million ha are preserved within Brazilian farms, representing 25.6% of the territory. Together with other conservation and preservation areas, the total preserved area amounts to 66% of the country.

Another critical compliance requirement of the New Forest Code is the enrollment of landowners in the Rural Environmental Registry (CAR, in Portuguese). This registry involves a self-declaration of georeferenced data on land use within farms, allowing governments to monitor deforestation and better plan rural areas while enabling farmers to access public services and policies, such as environmental grants and rural credit. However, the full implementation of CAR has been challenging, with progress slow in some states.

2.3.2. The ABC Program and the ABC+ Plan

In 2010, the Brazilian government launched the Low Carbon Agriculture Plan (ABC Plan), a greenhouse gas (GHG) emission mitigation strategy for the agricultural sector. The plan, expressed through Nationally Appropriate Mitigation Actions (NAMAs) to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), aimed to voluntarily reduce GHG emissions by 37% by 2025 and 50% by 2030, relative to 2005 levels (Brazil, 2012) [35]. Following the 2015 Paris Agreement, Brazil ratified and expanded its decarbonization targets with its Nationally Determined Contribution (NDCs).

Investments in the first phase of the plan (2010-2020) exceeded USD 3.5 billion, promoting low-carbon technologies such as recovery of degraded pastures, biological nitrogen fixation, no-tillage, integrated crop-livestock-forestry systems (ICLFS), agroforestry, planted forest, and livestock waste management. According to Santos et al. (2022) [36], the proportion of pastures with some level of degradation decreased from 71% in 2010t o 58% in 2018; ABIEC (2023) [2] reports that beef productivity in Brazil increased from 52 for 63 kg of carcass ha^{-1} between 2012 and 2020. Areas incorporating any combination of ICLFS expanded from 2 million ha in 2009 to 17 million ha by

[3] This mixed-system is known as "semi-intensive finishing".

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2020/2021 (Rede ILPF, 2020) [37], supassing the original target of 4 million ha by 2020 (Brasil, 2012) [35]. The ABC plan was extended until 2030 through the Sectoral Adaptation Plan for Low Carbon Agriculture for Sustainable Development (ABC+ Plan). This new cycle includes irrigated systems, intensive cattle finishing and the use of bio-inputs (Brazil, 2021) [38]. Given the potential of ICLS for diversifying and intensifying beef production while promoting GHG mitigation and improved water use (Almeida et al., 2013; Barsotti et al., 2022) [39,40], adoption of these production systems is expected to reach 35 million ha by 2030 (Rede ILPF, 2020) [37].

Additionally, in December 2023, the Ministry of Agriculture and Livestock announced the National Programme for the Conversion of Degraded Pastures into Sustainable Agricultural, Livestock and Forestry Production Systems (Decree 11.815), which promotes good agricultural practices to increase carbon capture (FAO, 2023b) [41]. The Programme's objectives include converting up to 40 million ha of degraded pastures into crops, planted forests or improved pasture, reducing deforestation pressure and contributing to food, feed and energy security while encouraging financial institutions and the capital market to develop financial opportunities (MAPA, 2023) [42].

2.4. Sustainable Intensification: The Path to Brazilian Low Carbon Beef

According to Bolfe et al. (2024) [43], approximately 110 million ha of pasture exhibit some level of degradation, representing about 60% of the total. Of these, 28 million ha are moderately or severely degraded but are situated on land suitable for crop production (Figure 2).

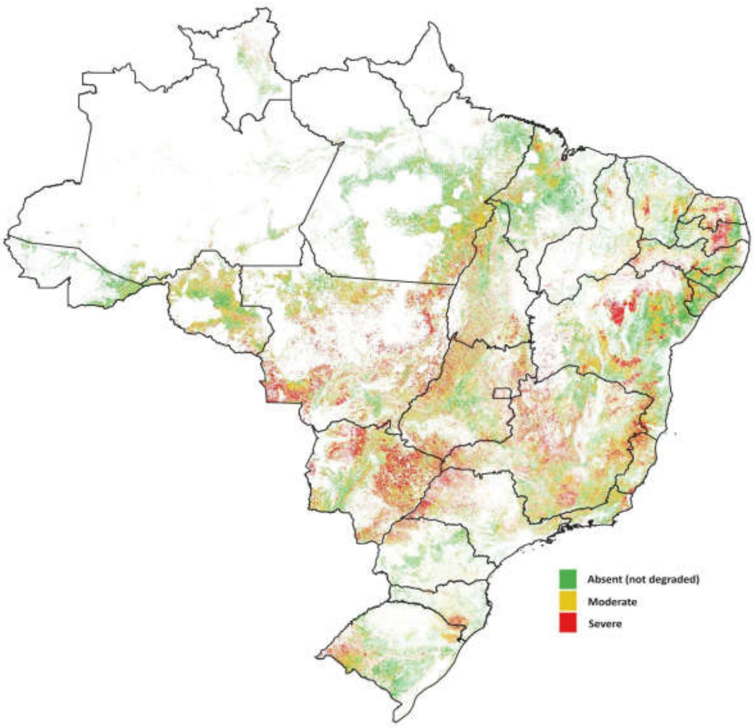

Figure 2. Pastures in Brazil according to three levels of degradation, 2022. Source: Prepared by the authors, based on Lapig database (2022) [44].

The three levels of degradation - absent (not degraded), moderate and severe (LAPIG, 2022a; MAPBIOMAS, 2022b) [44,45] - are defined relative to ideal yields for each pasture species (DIAS-FILHO, 2015) [46]. Pasture degradation primarily results from increasing grazing pressure and poor management, posing significant economic and environmental challenges. The higher the degradation level, the greater the recovery cost (Carlos et al., 2022) [47], which can be prohibitive for some farmers.

In response, there is growing appeal for the sustainable intensification of Brazilian agriculture and beef farming in particular. Bolfe et al. (2024) [43] argue that converting 28 million ha of degraded pasture, as encouraged by the National Programme for the Conversion of Degraded Pastures (MAPA, 2023) [42], could increase the total crop area by 35%, compared to the 2022/2023 crop season. Alternatively, recovering 30 million ha of pasture for improved beef farming would require an investment of USD 8.6 billion and could yield returns ranging from USD 440 million to USD 6.7 billion, depending on various beef price scenarios (Carlos et al., 2022) [47]. It is noteworthy that the development of beef farming also has spillover effects on regional prosperity, as evidenced by the Human Development Index (HDI) in a study by Lima et al. (2023) [17].

Given the high costs associated with recovering degraded pastures, farmers may opt for crop-livestock integration (Bolfe et al., 2024; Sekaran et al., 2021) [43–48]. This approach, sometimes incorporating trees, is known as integrated crop-livestock-forest systems (ICLFS). ICLFS can enhance yields, food security (Sekaran et al., 2021) [48], profitability, and reduce economic risks through production diversification (Cordeiro and Balbino, 2019) [49] while also creating new income opportunities, such as payments for environmental services and carbon credits (Malafaia et al., 2019) [50].

According to Rodrigues et al. (2023) [51], based on a comprehensive literature review, ICLFS are low-carbon agriculture models that provide ecosystem services related to nutrient cycling, biodiversity and soil erosion control. These benefits arise from the synergistic effects of ICLFS components on space and/or time. Integrating trees into the system allows for an average carbon accumulation of 30 kg tree^{-1} year^{-1} (equivalent to sequestrating 110 kg of CO_2 tree^{-1} year^{-1}) and enhances animal welfare by providing shade and shelter to cattle. Sekaran et al. (2021) [48] also highlight the system's increased resilience under global warming compared to specialized farms. It is important to note that these models can be adapted to any biome, climate condition, farmer types and market, although limitations such as infrastructure deficits and low farmer access to technical assistance and credit can hinder adoption (Arango et al., 2020) [52].

To encourage the adoption of good agricultural practices, including ICLFS, and to add value to beef, Embrapa has been developing beef farming protocols since 2005. Recently, concerns over beef GHG emissions have prompted the protocols to focus more specifically this issue. As a result, Embrapa developed the Carbon Neutral Brazilian Beef - CNBB (Alves et al., 2017; Lucchese-Cheung et al., 2021) [53,54] and the Low Carbon Brazilian Beef - LCBB (Almeida & Alves, 2020) [55], both aimed at increasing productivity while neutralizing or reducing methane emissions, respectively, by improving pasture management and applying Good Agricultural Practices (GAP), with or without planted trees. However, due to institutional challenges, the uptake of CNBB remains low and LCBB is going to be launched in 2024.

Given Brazil's renewed commitments to reduce GHG emissions by 50% by 2030 and achieve carbon neutrality by 2050 (UNFCCC, 2022) [56], addressing the challenges of implementing the aforementioned policies, programs and protocols is crucial. Overcome barriers, including socio-psychological factors such as cultural resistance, infrastructural issues like the absence of paved roads, bridges and warehouses, and institutional obstacles such as limited access to technology, credit and technical assistance is essential for further adoption of low-carbon technologies.

3. Discussion: Social Inclusion and other Challenges for the Brazilian Beef Farming

Despite significant growth in the Brazilian cattle sector and high expectations for further developments, numerous challenges persist. Arango et al. (2020) [52] argue that "reconciling the goals of benefiting from business and livelihood opportunities associated with cattle production while reducing [their] GHG emissions" is a challenge that governments are struggling with. Given the large size and distribution of the Brazilian cattle herd, this challenge is further amplified by uneven access to technology and knowledge. Nearly half of Brazil's five million rural establishments have cattle (IBGE, 2021) [57], dispersed throughout the country (Lima et al, 2023) [17]. Approximately 76% of these are smallholder farmers, who account for 31% of the total herd. These farmers often have little or no access to rural credit and technical assistance (Stabile et al., 2023) [33], making them particularly vulnerable to rural poverty (Buainain and Garcia Junior, 2018) [58]. The small scale of production also impacts the return on capital investment (Barreto, 2021) [59], perpetuating a cycle that keeps many of these farmers in a poverty loop, as depicted below (Figure 3).

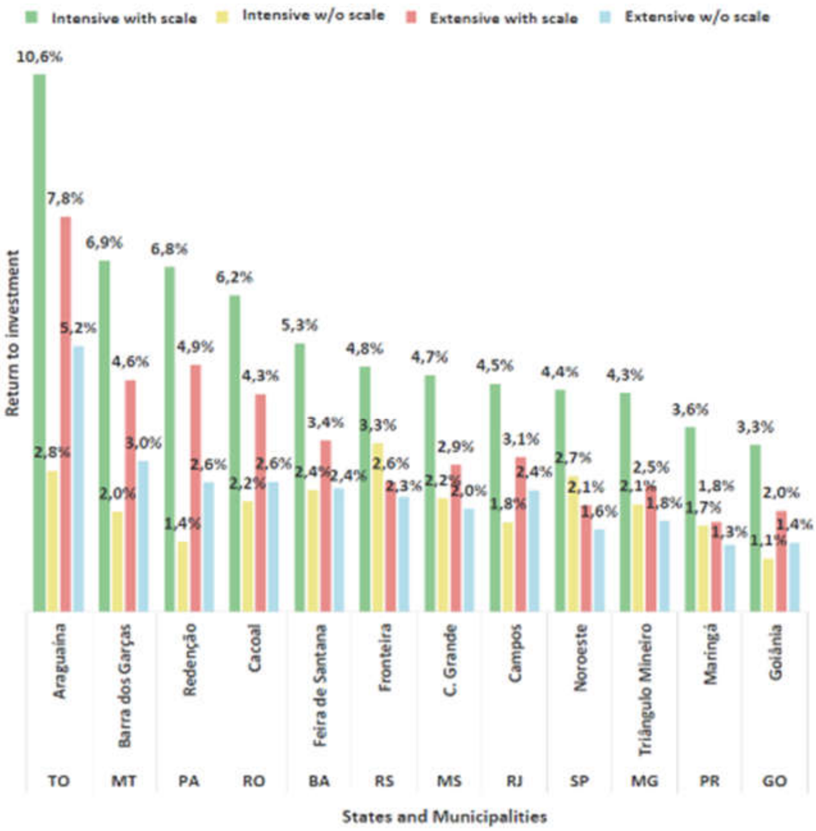

Figure 3. Return on capital (%) of rearing and fattening cattle with and without scale, and at different levels of intensification, in selected municipalities in Brazil, 2019. Source: Barreto (2021) [58].

Rising costs, driven by increased labor expenses and land appreciation, coupled with growing socio-environmental restrictions (Cortner et al., 2019; Nunes et al., 2019; Wetlesen et al., 2020) [60–62] are adding pressure on the economic margins of farms. Reports from Athenagro Rural Consultancy indicate that beef farmers with varying levels of technology began 2024 with cash reserves ranging from BRL 300/BRL 400 ha^{-1} (USD 57.8/USD 77.0) to BRL 750/BRL 1,200 ha^{-1} (USD 144.5/USD 231.1), depending on whether the farms had low or high technology uptake, respectively. The reports also revealed that high-technology farms accumulated deflated profits of BRL 25,000 to BRL 40,000 ha^{-1} (USD 4,815 - USD 7,704) over the last 25 years, while low-technology farms only managed between BRL 5,000 to BRL 10,000 ha^{-1} (USD 963 - USD 1,926) during the same period. These figures serve as proxies for the farmers' investment capacity to keep pace with sector technological advancements, suggesting that low-technology farms are at risk of market exclusion.

However, economic factors alone do not fully explain farmers' decisions on technology uptake (Pereira et al., 2016) [63]. Technology adoption also depends on the characteristics of technology itself and a range of personal, social and cultural factors (Pannell et al., 2006) [64], making it context-sensitive. Westbrooke and Nuthall (2017) [65] argue that small farmers' personality, personal characteristics, and objectives play a significant role in their decisions to maintain or expand their farms (e.g. increase area or intensify the production system). This aspect is often overlooked in research, particularly in Brazilian beef farming. The persistence of many small-scale farms in the country is frequently associated with public policies specifically targetting this group (Barreto, 2021)

[59], such as low-cost credit for family farms[4], minimum price policies, rural retirement pensions, allowances[5], and several others (Embrapa, n.d.) [66]. Therefore, despite reducing margins and increasing rural poverty, many small farmers persist.

The objectives and performance of Brazilian farms vary widely, spanning from subsistence to corporate farms: from low-input, traditional farming methods to precision farming that is highly market-oriented. Considering the diversity of contexts for cattle farming in Brazil (e.g., six biomes), it is not surprising that cattle production is so varied. More recently, however, Brazilian production models have been shifting toward more capital-intensive technologies (i.e. "land-saving" technologies) that offer better technical and economic performance (Marta Júnior et al., 2011) [67] and have lower environmental impact than traditional extensive systems (Molossi et al., 2020) [68].

Key technologies promoted for the sustainable intensification of beef production include ICLS and ICLFS, new forages, further genetic improvement of the herds, sound pasture management or recovery, feed supplementation, and good agricultural practices in general (Pelicano and Capdeville, 2021) [69]. ICLS and ICLFS, in particular, have great potential to transform Brazilian agriculture, as they promote training, higher agricultural income and better employment opportunities (Balbino et al., 2011) [70], in addition to increasing and diversifying agricultural production with lower environmental impacts. However, barriers to the adoption of such systems among beef farmers are anticipated, including cultural aspects (Garcia et al., 2017) [71]. Suggestions to overcome some of these barriers may include showcasing the profitability of the systems (Garcia et al., 2017) [71]; partnerships between beef and crop farmers (Gil et al., 2016; Carrer et al., 2020) [72,73]; shared risks and increased economic viability of integrated systems through farmers associations or cooperatives (Cechin et al., 2021) [74].

With the ongoing impacts of climate change, additional stress has been placed on production systems and their ability to generate regular income. The prospect of increasing beef production with less pasture, as prompted by the Federal Government (MAPA, 2023) [42] and with fewer labor resources available (Malafaia et al., 2021) [75], requires a transition from extensive to sustainably intensive beef farming reliant on technology adoption and on a supportive innovation system capable of accomodating the various farmer typologies that exist in Brazil. However, as Arango et al. (2020) [52] point out, in Latin America, financial resources are scarce, particularly for small to medium landholders which prevents many from implementing or maintaining sustainable technologies. Whether Brazil will be able to transition toward a sustainable intensification of beef farming in an inclusive manner remains an open question.

4. Conclusions

Beef farming is an important activity in rural Brazil, both from an economic and a social perspective, as it employs many people in the production and throughout its agrifood chain. It also provides nutritious food and byproducts for the Brazilian and the international markets, contributing to improving food security and the trade balance.

However, the environmental impacts and the technological inclusion of small to medium farms are concerns that need to be addressed. In this article, we have highlighted the strong development of Brazilian beef farming toward a sustainable intensification of production systems through the incorporation of many climate-friendly technologies. If decoupled from deforestation, beef production in Brazil has the potential to lower greenhouse gas emissions (de Oliveira Silva, 2016) [76], given the recovery of moderately to severely degraded pasture, enhancing the carbon sinks (Santos et al., 2024) [77].

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[4] In Brazil, the definition of family farms eligible to public policies with subsidized rates are: (i) have a total area of no more than four fiscal modules, which are variable in size according to the region; (ii) rely mostly on family labor; (iii) reach a minimum percentage of income coming from farming; and (iv) manage the farm with the family.

[5] For instance, the "Family Allowance" (*Bolsa Familia*, in Portuguese) is a public policy targeting rural and urban families whose members earn less than USD 44 per month each.

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Further progress is expected, but it may preclude some subgroups of farmers from keeping up to date with modern technologies, including digital technologies and precision livestock. For instance, how will the new traceability system, currently under discussion, affect small to medium farmers? Would they be able to cope on their own or will additional strategies and supporting conditions be needed? Further research should address these issues specifically.

When it comes to technology uptake, it is important to develop an extensive program of technical assistance and training to provide farmers and workers with new capabilities and enhance the social capital in farming. Financial and digital literacy, for instance, are becoming even more essential for further improvements of the sector. Without technical and economic knowledge, limited resources can be wasted, and little results achieved. Efforts should be directed and carried out by both private and public sectors to make them effective and to reach even those farmers, both male and female, in remote areas of Brazil.

For policymakers, it is crucial to recognize and consider some negative externalities of technological intensification of beef production and of the more strict environmental regulations in order to design sound strategies to include disadvantaged farmers. This may comprise alternative credit systems (i.e. microfinance), whereby smallholdings with low or no collateral can borrow increasing amounts of capital at low cost as they pay off prior borrowings, while progressively building their financial reputation with the banks or other financing institutions (e.g., cooperatives, farmers' associations). Better infrastructure is also needed to allow for better commercialization routes, both for inputs and outputs, access to markets and services, and communication systems. Ultimately, the speed of the sustainable intensification of the beef sector will be closely associated with the level of investments made in agriculture in general in the years to come.

BOX 1. *Cattle ranching in Pantanal - a special case of sustainable beef production.*

The Brazilian Pantanal biome is a 138,183 km^2 floodable area, with 65% in the state of Mato Grosso do Sul, and 35% in the state of Mato Grosso (Figure 4). It expands into Bolivia and Paraguay, where it is known as thje Chaco. It is the largest freshwater wetland in the world, a seasonally flooded lowland fed by the tributaries of the Paraguay River. Pantanal presents a great diversity of landscapes, associated with types of soil, degree of flooding and influence of the adjacent biome. Farming in this biome is challenging and unique.

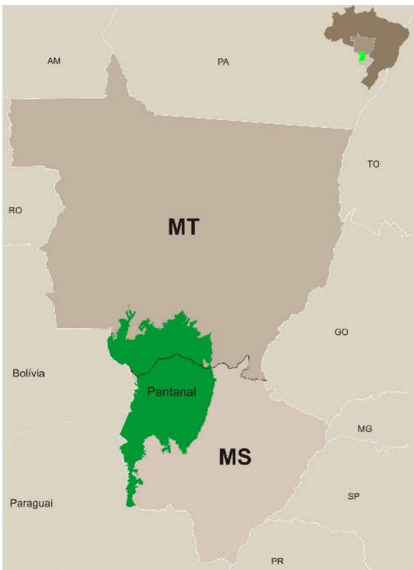

Figure 4. Map of the Pantanal biome, Brazil.

Natural grasslands are the basis of beef cattle ranching in Pantanal. Among domestic animals introduced by Spanish and Portuguese people are cattle (*Bos taurus*), donkeys (*Equus asinus*) and horses (*E. caballus*). Cattle farming in the Pantanal expanded significatly after the end of the gold panning era in the 19th century, spreading across the natural grasslands of the plain and remainsing the main economic activity in the region.

Originally, the herd consisted primarily of *Bos taurus taurus*, but it is now predominantly ocomprised of Zebu breeds, especially Nellore (*Bos taurus indicus*), due to the beef industry's preference - a process facilitated by the construction of the Northwest railway line in Brazil (Mazza et al., 1994) [78]. The breed's rusticity and adaptation to extreme weather conditions such as heat, periodic floods, and severe droughts, have favored its adoption. Crossbreeding with Angus, Brangus and Braford breeds can be also found on the edges of the plain. The area occupied by livestock has grown almost fourfold from 1985 to 2023. Despite this growth, Pantanal retains a coverage of natural vegetation between 80 and 85% (Guerra et al., 2020; MapBiomas, 2023) [79,80].

Approximately 93% of Pantanal's area is privately owned, and, unlike other biomes, it is predominantly characterized by large-acreage farms. About 12% of the farms encompass an area equal to or greater than 10,000 hectares (56% of the total Pantanal area), and 69% have areas ranging from 1,000 to 10,000 hectares (43% of the total area) (Cadavid-Garcia, 1986) [81]. The average stocking rate is 3.9 hectares per head (Silva et al., 2002) [82], reflecting the predominant extensive grazing system on natural grasslands (Abreu et al., 2019) [83]. Pantanal serves as a net provider of calves to highland areas, focusing on cow-calf farming (de Oliveira et al., 2016; Abreu et al., 2019) [76–83], with cattle management adapted to the flood regime (Pott et al., 1989) [84].

Farmers have gradually been improving native pastures by introducing African grasses, which increase carrying capacity of Pantanal farms, thus enhancing typically low yield rates. Other technologies for farm management, cattle reproduction, nutrition, and genetics have enabled further efficiency improvements (Abreu et al., 2022) [85]. Interestingly, the objective of Pantanal conservation depends on strengthening the sustainable development of traditional cattle farming in the region (Abreu et al. 2022) [85]. Due to its importance in the regional economy and the local tradition of natural resources conservation, Pantanal cattle farming can provide high levels of sustainability (Guerreiro et al., 2019; Schulz et al., 2019) [86,87]. This is further enabled by the low population density in Pantanal (around 30,000 people), which prevents greater pressure on natural resources.

There is an opportunity to increase efficiency of cattle production in the biome by maximizing *sustainable profit* per hectare. However, this must come from the adoption of locally designed technologies for sustainable intensification (Abreu et al., 2018) [88] and should consider multiple socioeconomic aspects, as well as different environmental dimensions (Schulz et al., 2019) [85]. Various projects have been carried out in "real farming" systems to develop and promote the adoption of technologies and monitor animal, economic, and environmental outcomes (Abreu et al., 2012; Oliveira et al., 2014; Bergier et al., 2019; Nogueira et al., 2019; Rodrigues et al., 2019; Abreu et al., 2022) [85–89] to enable the sustainable intensification of cattle farming in the region. However, traditional methods of technology transfer have not been effective in increasing adoption, suggesting the need for new strategies to engage farmers locally.

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Data Availability Statement: The datasets we used to build our maps are publicly available at the following links: https://www.ibge.gov.br/explica/producao-agropecuaria/bovinos/br (Figure 1 - Cattle herd);

https://lapig.iesa.ufg.br/p/38972-atlas-das-pastagens (Figure 2 - Pasture distribution with different levels of degradation).

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