Brazilian Agriculture and Climate Change: Sectoral Scenarios Based on the Shared Socioeconomic Pathways (SSPs)

Agricultura Brasileira e Mudanças Climáticas: Cenários Setoriais baseados nos Caminhos Socioeconômicos Compartilhados (SSPs)

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Abstract: Despite progress in agricultural productivity, sustainable land management, and low-carbon energy transitions, Brazil's farming sector remains significantly exposed to the risks posed by climate change. Rising temperatures, increasing water scarcity, and more frequent extreme weather events are expected to place growing pressure on national agroecosystems. This paper introduces the AGROBR-SSPs (Agricultural Pathways for Brazil under the Shared Socioeconomic Pathways framework), a collection of qualitative, region-tailored scenarios built through a top-down downscaling methodology applied to the global SSPs. The narratives capture Brazil's distinct socio-environmental and institutional realities, incorporating dimensions such as governance structures, economic trajectories, and shifting societal behaviors. The AGROBR-SSPs are designed to support integrated assessments of land use dynamics, crop yield projections, environmental pressures, and fossil fuel dependency. By anchoring national development pathways within a globally recognized framework, this research contributes to the design of climate-resilient policies and enhances the long-term adaptability of Brazil's agri-food systems through 2050.
Keywords: climate change, shared socioeconomic pathways, Brazilian agriculture, scenario analysis, climate adaptation.

Resumo: Apesar dos avanços em produtividade agrícola, manejo sustentável do solo e transições energéticas de baixo carbono, o setor agropecuário brasileiro permanece significativamente exposto aos riscos impostos pelas mudanças climáticas. A elevação das temperaturas, o agravamento da escassez hídrica e a maior frequência de eventos climáticos extremos tendem a exercer pressão crescente sobre os agroecossistemas nacionais. Este artigo apresenta os AGROBR-SSPs (Trajetórias Agrícolas para o Brasil no âmbito dos Caminhos Socioeconômicos Compartilhados), um conjunto de cenários qualitativos e regionalmente diferenciados, construídos por meio de uma metodologia de downscaling top-down aplicada aos SSPs globais. As narrativas desenvolvidas refletem as especificidades socioambientais e institucionais do Brasil, incorporando dimensões como estruturas de governança, trajetórias econômicas e transformações nos padrões de comportamento social. Os AGROBR-SSPs foram concebidos para subsidiar avaliações integradas sobre dinâmicas de uso do solo, projeções de produtividade agrícola, pressões ambientais e dependência de combustíveis fósseis. Ao articular trajetórias nacionais de desenvolvimento com um framework globalmente reconhecido, a pesquisa contribui para a formulação de políticas climáticas resilientes e para o fortalecimento da capacidade adaptativa dos sistemas agroalimentares brasileiros até 2050.
Palavras-chave: mudanças climáticas, caminhos socioeconômicos compartilhados, agropecuária brasileira, análise de cenários, adaptação climática.

1. Introduction

In recent decades, the construction of future socioeconomic scenarios has become a tool to address challenges related to global climate change. Within this context, Shared Socioeconomic Pathways (SSPs) form a conceptual and methodological framework based on five qualitative narratives that describe plausible development trajectories, quantified through integrated assessment models (IAMs) (O'Neill et al., 2014; Riahi et al., 2017). Although originally developed at global and regional scales, their application to impact, vulnerability, and adaptation analyses at national and sub-national levels depends on contextualization. Here, SSPs are used as illustrative global pathways that serve as boundary conditions for regional extensions (Pedde et al., 2025), offering an accessible starting point for studies focused on local adaptation and bottom-up perspectives (Pedde et al., 2025; Wilbanks, Ebi, 2014).

The regionalization of SSPs remains a major challenge, as it requires adapting global scenarios to local contexts by incorporating social, political, economic, and environmental specificities not captured in their original formulation. Brazil presents marked sociocultural diversity, high urbanization, significant inequalities, and a strategic role in global environmental governance, particularly due to the Amazon, which reinforces the need for narratives that reflect its regional and institutional complexity.

This study focuses on Brazil's agribusiness sector, given its contribution to GDP, leading role in exports, and influence on political and environmental dynamics. Examining its dynamics, vulnerabilities, and transformations supports understanding national development pathways and responses to climate change. The study develops five contextualized SSP narratives for Brazil by adapting the global assumptions of (O'Neill et al., 2014) to the country's social, institutional, economic, and environmental conditions. While SSPs were designed to support CMIP6, their national application may be limited in contexts such as Brazil, characterized by regional inequalities and complex institutional and sectoral structures. To address this, the study proposes a qualitative extension that integrates region-specific trends into global narratives (Zanderson et al., 2019), using SSPs as boundary conditions that guide regional unfolding. This approach follows the "Adaptation First" category (Pedde et al., 2025), emphasizing local responses and adaptation strategies.

The narratives incorporate dimensions such as demography, human development, economic growth, lifestyles, public policies, institutional regimes, and emerging technologies, with emphasis on environmental aspects and natural resources, particularly agriculture and land use. Their construction follows six quality criteria proposed by (O'Neill et al., 2014; Alcamo, 2001; Mitter et al., 2019): plausibility, internal consistency, salience, legitimacy, descriptive richness, and creativity, aiming to support integrated analyses of mitigation, adaptation, and public policy at the national level.

2. Literature Review

The construction of environmental narratives follows structured methodological protocols, typically organized into three phases: organizational steps, narrative development and quantification, and synthesis, review, and dissemination. The literature emphasizes the need to downscale global Shared Socioeconomic Pathways (SSPs) to regional and sectoral contexts to enhance their relevance for local decision-making (Mitter et al., 2001; Alcamo, 2008; Lehtonen, 2021). In Brazil's agricultural sector, this process adapts global scenarios to national environmental, institutional, energy, and technological conditions while preserving consistency with global assumptions. Tebaldi and O'Neil (2020) characterize these adaptations as "extended SSPs," which incorporate sector-specific detail without departing from overarching global narratives, particularly in contexts marked by regional heterogeneity and governance variation.

In the context of Brazil's agricultural sector, downscaling translates general global scenarios into region-specific, plausible projections that align with Brazilian agricultural realities. This localized approach provides a clearer picture of the challenges, vulnerabilities, and adaptation potential in different regions of Brazil's agribusiness sector. Integrating global Shared Socioeconomic Pathways (SSPs) with regional downscaled data makes it possible to assess the necessary mitigation and adaptation efforts. These efforts may include technological innovations, such as mechanization; levels of crop management; genetic improvements; and policies that promote climate resilience and adaptation.

Moreover, downscaling allows for the development of specific public policies at various levels, federal, state, and municipal, by identifying areas of concentrated effort, determining plausible trajectories based on current trends, and recognizing regions in need of increased political and economic mobilization. This approach also illustrates how different socioeconomic futures, as defined by SSPs, can affect the capacity for adaptation and the costs of Brazil's agriculture. Developing indicators that can track adaptive efforts and measure the efficacy of adaptation policies over time is a crucial step in this process.

Studies stress that downscaling is central to sectoral climate planning, as it links socioeconomic pathways to agricultural outcomes and supports the design of adaptation and mitigation strategies. Ebi et al. (2014) note that while some global drivers exert consistent effects, local dynamics may diverge, requiring approaches that balance global coherence with contextual specificity. Accordingly, global scenarios are interpreted as constraints rather than deterministic outcomes, guiding the development of locally plausible narratives and reinforcing the need for interdisciplinary collaboration across fields such as agronomy, economics, climatology, and policy analysis.

It is evident that global scenarios do not determine regional outcomes. Rather, they function as constraints that guide locally plausible narratives. This necessitates interdisciplinary collaboration to address agricultural challenges. These efforts yield scaled-down SSPs as decision-support tools, developed through three phases: formation of expert groups, narrative construction and quantification with peer review, and dissemination with validation by experts and end-users (Mitter et al., 2001; Alcamo, 2008; Lehtonen, 2021).

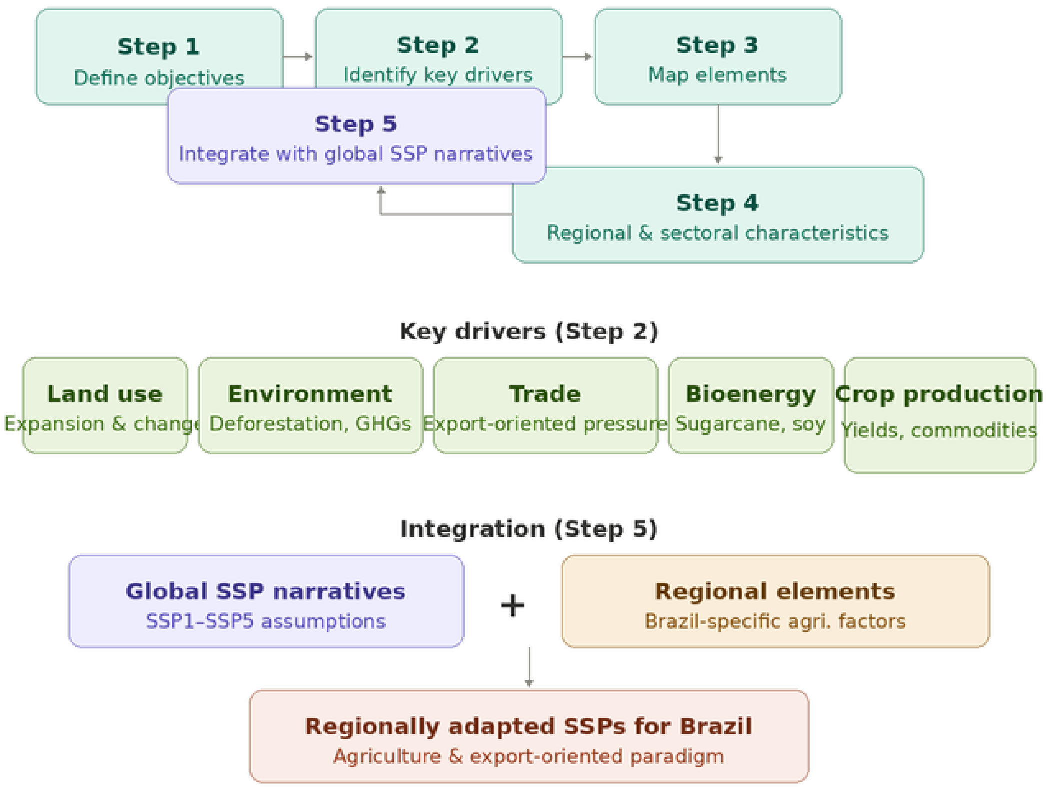
The construction of plausible environmental scenarios requires the application of well-defined quality criteria to ensure the scientific relevance, practical utility, and social legitimacy of the resulting narratives. To meet these standards, six core dimensions must be considered in assessing the quality of the narrative of the scenario: plausibility, consistency, importance, legitimacy, richness, and creativity (O'Neill et al, 2014; Alcamo,2008).

Plausibility refers to futures that are possible, logically defensible, and causally coherent. Consistency concerns internal coherence across scales, with smaller-scale narratives enhancing spatial and thematic resolution and enabling actor identification (O'Neill et al., 2014). Salience ensures scenarios are clear and accessible to target users. Legitimacy integrates diverse knowledge forms, including scientific, empirical, traditional, and institutional, ensuring representativeness and transparency. Richness captures a broad range of futures, identifying adaptation and mitigation challenges. Creativity reflects narrative diversity and originality (O'Neill et al., 2014; Mitter et al., 2019; Lehtonen et al., 2021; Karner et al., 2024; O'Neill et al., 2016; O'Neill et al., 2017). Throughout the design process, subject matter experts were consulted to ensure plausibility and alignment with SSP trajectories adapted to the Brazilian agricultural context.

3. Methodology

To construct regionally adapted SSPs for Brazil, focusing on agriculture, a five step framework was applied: (1) defining objectives; (2) identifying key drivers shaping Brazilian agriculture under an export oriented paradigm, such as land use, environmental impacts, trade pressures, bioenergy, and crop production; (3) mapping these elements; (4) identifying regional and sectoral characteristics; and (5) integrating regional elements with the assumptions of global SSP narratives. The Figure below shows this process:

Figure 1 – Five-step framework for regionally adapted SSPS to the Brazilian Agricultural System



Source: own elaboration.

This methodological approach builds on the process used to develop the original SSP narratives[1] but adds a step: identifying regional and sector-specific characteristics following the adaptation proposed by Rakovic et al (2020). This enhancement allows for more meaningful downscaling of SSPs to Brazil, where institutional specificities are crucial in shaping agrarian policy frameworks.

3.1 Define objectives.

This study aimed to develop future-oriented AGROBR-SSPs to support assessments of agricultural transformation pathways through 2050. The development was based on a

[1] see (O'Neill et al, 2014; Lehtonen, 2021).

comprehensive evaluation of macro-level and sector-specific drivers shaping long-term agricultural trajectories in Brazil. Key factors such as demographics, human development, economic growth, lifestyle patterns, policy frameworks, technological progress, and environmental resources were incorporated. In this way, national narratives were aligned with global SSP assumptions while maintaining contextual relevance.

The narratives incorporated sector-specific elements critical to Brazil's agricultural evolution, including socioeconomic inequality, international trade dynamics, globalization, dietary shifts, and international cooperation. The design of the scenario was informed by policy domains such as environmental regulation, institutional development, technology transfer, and bioeconomy and energy orientations. A thorough examination of bioenergy deployment factors was undertaken, encompassing drivers such as technological advancements, shifts in carbon and energy intensity, constraints on fossil resources, land-use change, agricultural productivity, and crop and forestry systems.

The AGROBR-SSPs articulate plausible trajectories for Brazilian agriculture, ensuring methodological consistency while being specifically tailored to reflect the contextual realities of Brazil's rural landscape. These narratives provide a robust foundation for stakeholder engagement and policy formulation aimed at fostering a resilient and sustainable agricultural sector, amid climatic uncertainty, environmental constraints, and increasing sustainability demands.

3.2 Identify key elements.

The AGROBR-SSP narratives were constructed by first identifying the key elements outlined by O'Neill et al. (2015). These elements include demographic dynamics, economic growth, technological progress, and environmental constraints. These elements were contextualized using global SSP logic, which differentiates pathways based on income groups and fertility rates (KC and Lutz, 2014). To this study, the assumptions pertaining to Brazil were modified to reflect distinct demographic trends, including fertility rates, migration patterns, urbanization, educational attainment, and the nation's role in international trade.

This sectoral analysis synthesizes the general socioeconomic assumptions from the initial stage, connecting them to a comprehensive interpretation of Brazil's agricultural economy under each of the five SSP scenarios. It captures the evolution of key variables across domains such as land use, production systems, technology adoption, institutional change, and trade. This enables a coherent representation of plausible futures for the country's agricultural sector.

3.3 Identify regional drives and sectoral characteristics.

The first methodological step involved identifying the structural assumptions of the Shared Socioeconomic Pathways (SSPs) concerning demographic, socioeconomic, and institutional factors, based on O'Neill et al. (2015). The analysis focused on countries with high fertility rates (KC and Lutz, 2014) and middle-income economies, as classified by the World Bank, reflecting the Brazilian context in terms of population and economic development.

Building on this foundation, a qualitative downscaling of the SSPs to the Brazilian context was conducted, focusing on the agricultural sector. The methodology followed a structure like that of Alcamo (2008), Mitter et al. (2020), Lehtonen et al. (2021), and Rakovic et al. (2020) combining global narratives, regional adaptation, and identification of key sectoral impact drivers. This process led to the identification of the main drivers influencing Brazilian agriculture.

The identification of these drivers occurred in two stages. First, relevant elements for Brazilian agriculture were mapped to the core components of the SSP. Then, for each SSP element, its specific features in the Brazilian context were described, considering regional and sectoral dimensions. This step drew on national literature and consultations with experts in agriculture, rural development, and public policy.

It is important to note that some elements were considered primary social drivers of future agricultural development in Brazil (e.g., demographic dynamics, technological advancement, and access to credit), while others were treated as implicit assumptions, reflecting the global logic of each SSP. For example, in developing BRSSP1, aligned with SSP1, implicit assumptions included strengthened institutions, higher educational attainment, increased environmental awareness, and facilitated technology diffusion. These assumptions align with SSP1's internal logic and were incorporated to maintain narrative coherence between global and national levels.

3.4 Combine elements.

As previously noted, key elements of the BRSSPs were aligned with the global SSP framework to ensure consistency. These elements guided the mapping of relationships across three scales: global, national (Brazil), and sectoral (agriculture). All SSP elements and assumptions were sourced from O'Neill et al. (2017) with supplementary data from KC and Lutz (2014) and Riahi et al. (2017). In addition, empirical studies served as critical sources for the narrative construction of the BRSSPs, providing regionally specific insights into key sectoral dynamics. These included research on land use and land cover scenarios (Gomes et al., 2020), rural outmigration in Northeast Brazil (Delarezi et al., 2022), and water availability in the Brazilian Cerrado (Siqueira et al., 2021). This multi-scale mapping and narrative development approach offers a grounded framework for translating global socioeconomic scenarios into context-specific pathways.

However, in the mapping exercise to inform the BRSSPs, all the elements and assumptions of the SSP were considered. Within the conceptual framework of this study, one of the elements of the SSP was expanded to meet specific research criteria related to the Brazilian agricultural sector. Within the overarching thematic category of "Environment and Natural Resources" the component "Agriculture" encompasses two subcomponents. The initial component pertains to the enhancement of on-farm management techniques, drawing upon EMBRAPA's categorization of technological management levels as a method to mitigate climate-related risks, as outlined in the work of Debiasi et al. (2022).The second component refers to the structural and organizational aspects of agriculture in Brazil, including access to credit, input use, technological investment, and prevailing production models.

EMBRAPA's framework identifies four levels of agricultural management, with Level 4 representing the most advanced. This level includes practices such as crop rotation, soil correction and conservation, the use of modern inputs, and access to high quality agricultural infrastructure. However, the feasibility of adopting such advanced management implicitly depends on a well-functioning and coordinated institutional environment. This includes the provision of rural credit for machinery acquisition, the availability of technical assistance and extension services, effective public policies, increased environmental awareness among producers, and elevated levels of education within the rural workforce.

The decision to incorporate the "agriculture" element was made with the objective of more accurately and plausibly reflecting the systemic complexity of Brazilian agriculture. It acknowledges that effective climate resilient farming does not rely solely on on-farm decisions, but also on broader structural and institutional conditions that shape their implementation. This approach follows the methodological guidance of Alcamo (2008), which emphasizes the importance of disaggregating key variables in contexts where narrative plausibility depends on capturing interdependent factors in a realistic manner.

All mappings aimed to extrapolate trends based on the core SSP assumptions to construct plausible socioeconomic trajectories for Brazilian agriculture. In some cases, addressing themes such as economic growth, lifestyle (per capita), policies, institutions, technology, and environmental resources required extending the original SSP elements beyond current literature.

Although these categories are present in the global narratives (O'Neill et al., 2017), they often provide only general descriptions, limiting their direct applicability to regional or sectoral contexts. Given the importance of agriculture in this study, these categories were disaggregated into more specific sub elements, following a methodology similar to Rakovic et al. (2020), who also advocated for decomposing SSP components in regional downscaling.

4. Results and Discussion

The identification of key scenario elements, mapping BRSSP components to SSP drivers, and formulating trends for each BRSSP elements form the basis for the textual description of each pathway. The following subsections present these descriptions for the five BRSSP narratives — SSP1 (Green Road), SSP2 (Middle of the Road), SSP3 (Rocky Road), SSP4 (Inequality), and SSP5 (Fossil-fueled Development).

The narratives offer an overview of the potential implications for Brazilian agriculture in 2050, assuming global socioeconomic developments follow trajectories like the corresponding SSPs for Brazil. Each BRSSP description includes a brief explanation of how its future trajectory could emerge based on the trends in Table 1 and the main differences between pathways.

In SSP1 (Green Road - Innovative and Sustainable Agriculture), agriculture is sustainable and technologically advanced, prioritizing environmental conservation and climate adaptation. SSP2 (Middle of the Road- Staying the Course) features moderate growth with gradual improvements but faces regional inequalities and institutional constraints. SSP3 (Rocky Road - Rivalries and Climate Vulnerability in Agriculture) struggles with low innovation, fragmented policies, and resource-intensive expansion, increasing climate vulnerability. SSP4 (Inequality - Inequality in Brazilian Agribusiness) depicts a divided sector, with significant disparities between large farms and smallholders, undermining resilience. SSP5 (Fossil-fueled Development - Economic Progress Fueled by Fossil Energy) emphasizes rapid growth through intensive mechanization and fossil fuel use, leading to environmental damage and sustainability risks.

4.1 SSP1 - Innovative and Sustainable Agriculture

The SSP1 scenario for Brazilian agriculture emphasizes strong adaptation and mitigation capacity, driven by investments in green technologies and sustainable practices. The productive sector actively engages in low-carbon policies, green financing, and incentives for clean technology adoption.

Technological adoption is evident in the dominance of NM4 and NM3 management levels, which enhances resilience and mitigation. NM4, representing the highest sustainable management, covers about 75% of agricultural land, focusing on innovative practices, advanced infrastructure, and heightened environmental awareness. Lower management levels, especially NM1, are nearly nonexistent, indicating a shift to modern, efficient systems. In terms of mechanization, agricultural practices have significantly improved planting efficiency, with a 15-20% increase in tractor use, optimizing the planting window by up to 30%. This reduces crop exposure to adverse conditions, such as droughts or heavy rainfall, enhancing productivity, especially in regions with shorter growing seasons. Biotechnology plays a key role, with investments in genetically modified soybean cultivars that feature 90–100-day cycles and improved water-use efficiency. These cultivars are drought-resistant and adapted to future climatic variations.

To ensure water sustainability, the scenario incorporates advanced precision irrigation, rainwater harvesting, and bio irrigation, enhancing water efficiency. Soil conservation practices that improve infiltration and enable double cropping (e.g., soybean-maize) are widely implemented, reducing climate vulnerability and boosting annual productivity.

From an economic perspective, while the initial costs for advanced technologies and sustainable infrastructure are high, the subsequent costs of adaptation are significantly reduced over time. The adoption of green technologies has been demonstrated to facilitate low-cost adaptation with higher returns. This phenomenon is driven by two factors: the mitigation of climate disaster impacts and the enhancement of production efficiency. Strategic investments prioritize research and innovation, encompassing the development of climate-resilient cultivars, bio-inputs, and integrated pest management methodologies, with the objective of reducing synthetic agrochemical utilization. Public policies offering tax incentives and subsidies are crucial for advancing mechanization, agroforestry systems, and precision irrigation.

The provision of support for applied research and local adaptation solutions serves to enhance the capacity of crop farmers to adopt low-carbon systems. This, in turn, fosters the development of a resilient, innovative, and sustainable agricultural model by 2050.

Figure 2 – The Green Path (SSP1)

Source: own elaboration.

4.2 SSP2 - Staying the Course

SSP2, also known as "Staying the Course," delineates a global development trajectory that entails moderate challenges mitigation and adaptation of climate change. In the context of Brazilian agriculture, SSP2 signifies a balanced growth trajectory, characterized by technological and institutional progress, though less pronounced and coordinated than under SSP1. Consequently, the agricultural transition in SSP2 is marked by structural disparities and gradual development. In the context of SSP2, Brazilian agriculture is characterized by a heterogeneous distribution of Management Levels (NM), with NM3 systems predominating—intermediate production systems using established practices and moderate technological integration. A gradual shift toward NM4 is indicated, suggesting an increase in technical capacity and efficiency. However, disparities persist across regions and sectors.

A considerable proportion of farms continue to operate within the NM2 category, where practices are less intensive and more susceptible to climatic and market variability, reflecting persistent structural inequalities. The implementation of modernization initiatives, evidenced by investments in moderate mechanization, including an augmented tractor fleet, has led to a substantial increase in plant efficiency. This approach is further bolstered by the integration of adaptive genetics, exemplified by the adoption of soybean cultivars characterized by abbreviated growth cycles (approximately one hundred days). These cultivars serve to shorten the duration of cropping season intervals, thereby facilitating more intensive land use. This is noteworthy considering the challenges posed by constrained public funding and limited institutional support when compared to the SSP1 framework. The planting speed can be increased to optimize climatic windows and stabilize yields, particularly in regions transitioning between agricultural, forest, and pastoral systems. However, the operational improvements under SSP2 are more gradual than in ambitious scenarios like SSP1, due to limited integration of public policy, agricultural financing and agroclimatic research. Water management in SSP2 prioritizes efficiency and conservation but lacks the advanced automation of high-sustainability scenarios.

The adoption of efficient irrigation systems, such as drip and pivot systems, is gradually increasing, along with enhanced water storage and harvesting methods, such as small dams and community reservoirs. Nonetheless, resilience to extreme climate events remains constrained, especially in regions with limited institutional capacity for adaptive planning. Despite the expansion of adaptive practices, climate risk remains critical, especially in regions prone to prolonged droughts or extreme hydrological events. Water management remains reactive rather than preventive, with long-term strategies hindered by weak policy coordination and limited financial resources. While SSP2 does not represent stagnation, it presents moderate challenges to the sustainability of the agri-food system. Addressing these challenges requires coordinated public policies to support the transition from NM2 to NM4, strengthen innovation networks, and improve climate resilience at multiple scales.

In the short term, adaptation costs are moderate, with investments focused on conventional mechanization and water infrastructure in high-productivity areas. However, the lack of advanced technologies and systemic integration increases marginal costs as climate impacts intensify. Long-term adaptation costs increase due to the need for continuous upgrades to agricultural and water infrastructure in response to increasing rainfall variability and extreme weather events. The expansion of agricultural insurance and disaster mitigation funds, combined with increased climate risks, adds pressure. Restoration of degraded land, particularly in water scarce regions like the Cerrado and MATOPIBA, and reliance on the private sector for innovation financing further increase costs, especially for small and medium scale producers. Under SSP2, public policies are reactive and selective, emphasizing gradual adaptation and region-specific incentives. The implementation of support programs for sustainable technologies, including agroforestry, precision agriculture, and integrated nutrient management, occurs on a limited scale. The concept of green finance is undergoing a gradual expansion, with the adoption of this approach being facilitated through public-private partnerships. While sustainable credit lines and climate risk sensitive insurance are vital for sectoral competitiveness, financial institutions face challenges in risk pricing and ensuring equitable access.

Figure 3 – Staying the course (SSP2)

Source: own elaboration.

4.3 SSP3 - Rivalries and Climate Vulnerability in Agriculture

Under Shared Socioeconomic Pathway 3 (SSP3), or “Regional Rivalry,” the Brazilian agricultural sector encounters profound structural barriers to both climate change mitigation and adaptation. Characterized by limited international cooperation, economic stagnation, and deepening social inequality, this scenario constrains institutional capacity, public investment, and technological innovation.

Agricultural activity remains at low management levels (NM1 and NM2), especially among small and medium-scale producers operating extensive, low-input systems with limited adaptive capacity. The progression toward advanced management (NM4) is hindered by weak governance, inadequate public support, and a lack of extension services. Technological stagnation further impairs planting efficiency, reflected in sluggish mechanization and restricted access to key biotechnologies, such as drought-resistant and short-cycle soybean cultivars. Consequently, productivity stagnates, and planting calendars become increasingly misaligned with growing climate variability.

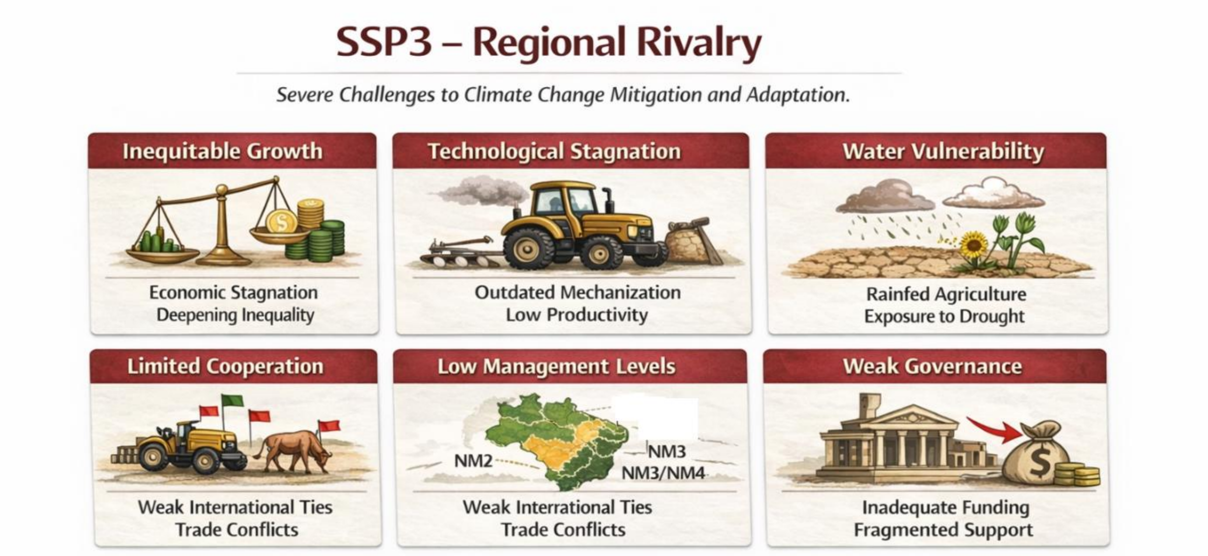
Under SSP3, the rudimentary water management—characterized by inadequate irrigation and minimal uptake of monitoring and conservation technologies, which renders rainfed agricultural systems highly susceptible to rainfall variability. This vulnerability is particularly pronounced in climate-sensitive areas like the MATOPIBA frontier, where systemic weaknesses exacerbate exposure to intensifying extremes such as prolonged droughts and heavy precipitation events.

Although initial adaptation costs may seem low, they reflect constrained financial and institutional capacity rather than adaptive efficiency. Chronic underinvestment in infrastructure and technology exacerbates vulnerability, as outdated systems drive rising adaptation costs amid intensifying climate impacts. These burdens fall disproportionately on smallholders who lack access to credit, insurance, or technical support, while large agribusinesses— with capital and proprietary technologies— maintain competitiveness.

The structural rural inequality deepens as only capitalized agribusinesses with access to insurance and proprietary technologies remain competitive, while smallholders confront escalating barriers to adaptation and viability. Public interventions, where they exist, are reactive and limited in scope, offering fragmented support insufficient for sustaining long-term sectoral resilience.

In essence, under the SSP3 scenario, Brazil remains a major commodity exporter but does so amid heightened climate risks, low productivity, and rising crisis management costs. Adaptive capacity is limited, with short-term responses, shaped by fiscal austerity and weak institutional coordination. Without structural reforms in governance, investment, and technology diffusion, agricultural resilience remains fragile and unevenly distributed.

Figure 4 – Regional Rivalry (SSP3)



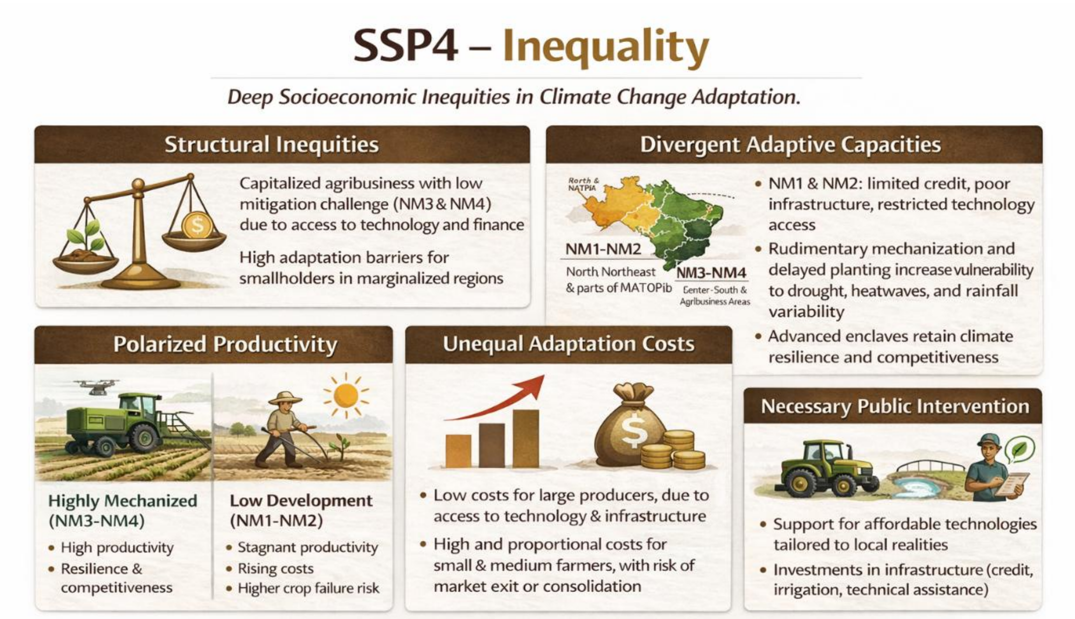
Source: own elaboration.

4.4 SSP4 - Inequality in Brazilian Agribusiness

Under SSP4 ("Inequality"), Brazilian agriculture is shaped by deep sociospatial and economic asymmetries. Mitigation challenges are limited for capital-intensive agribusinesses operating at higher management levels (NM3 and NM4), due to access to advanced technologies and finance. However, adaptation barriers are high— particularly for smallholders in marginalized regions. In areas such as the north, northeast and parts of MATOPIBA, production remains limited to NM1 and NM2, marked by limited credit, infrastructure, and technological access. In this region, the combination of rudimentary mechanization and delayed planting increases the vulnerability of agricultural systems to climatic stressors, such as droughts, heatwaves, and variability in rainfall patterns.

The diverging adaptive capacities under SSP4 create a polarized agricultural landscape: while technologically advanced enclaves retain climate resilience and competitiveness, less developed regions face stagnant productivity, rising costs, and greater crop failure risk. Small and medium producers bear disproportionate adaptation burdens, often leading to market exit or consolidation. Targeted public intervention is essential to prevent deepening rural inequality, including support for affordable, locally appropriate technologies, infrastructure, and technical assistance. Absent such measures, growing intra-sectoral disparities threaten regional food security, rural livelihoods, and the overall resilience of Brazilian agriculture to climate change.

Figure 5 – Inequality (SSP4)



Source: own elaboration.

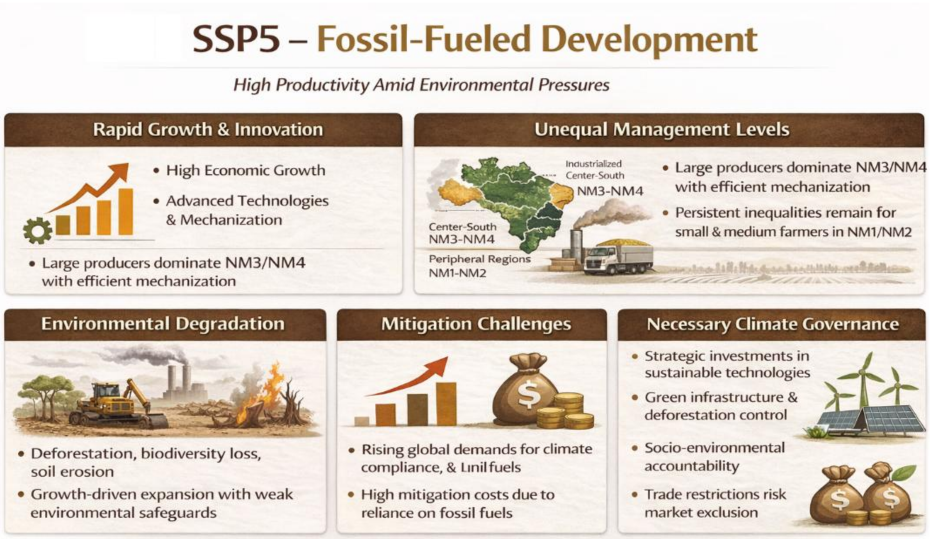
4.5 SSP5 - Economic Progress Fueled by Fossil Energy

Under SSP5 — characterized by strong economic growth, rapid technological progress, and sustained dependence on fossil fuels —Brazilian agriculture achieves unprecedented productivity. The challenges associated with adaptation are minimal due to the presence of robust financial capacity and infrastructure. However, mitigation becomes critical amid rising greenhouse gas (GHG) emissions and weak environmental regulation. The large producers dominate in NM3 and NM4, leveraging advanced mechanization, efficient irrigation, and genetically improved cultivars. Nevertheless, small, and medium farmers, especially in peripheral regions, remain at NM1–NM2, underscoring persistent inequalities in access to technology and capital.

The intensive and mechanized model under SSP5—marked by heavy use of nitrogen fertilizers, pesticides, and road transport—drives significant GHG emissions, increasing Brazil's reputational and trade risks amid rising global demands for environmental compliance. Although technological capacity keeps adaptation costs low, long-term mitigation costs are expected to increase. Advanced water management improves short-term efficiency but strains natural resources, undermining sustainability. Agricultural expansion, driven by growth-oriented priorities and weak environmental safeguards, contributes to deforestation, biodiversity loss, and higher carbon intensity. While Brazil remains a key global agro-industrial exporter under SSP5, sustained competitiveness will hinge on meeting rising demands for climate transparency, environmental certification, and socio-environmental governance. Failure to comply with these regulations may result in trade restrictions and market exclusion. Strategic investments in sustainable technologies, green infrastructure, and integrated adaptation policies are essential to align productivity with long-term environmental integrity.

Consequently, SSP5 anticipates a future of high agricultural output, characterized by environmental fragility and the necessity of effective climate governance to mitigate systemic risks. The implementation of downscaled SSPs within the context of Brazilian agriculture facilitates the conversion of comprehensive global scenarios into sector-specific, regionally specific projections. This approach enhances the capacity to identify localized vulnerabilities, adaptive potential, and policy-relevant intervention points in Brazil's diverse agroecosystems. By aligning these pathways with the realities of Brazilian agriculture, it becomes possible to trace the distinct technological, institutional, and financial efforts required under each scenario, as well as the spatial and socioeconomic implications of climate adaptation and mitigation strategies. This process also serves as a valuable entry point for engaging leading agricultural researchers in Brazil who may be unfamiliar with the SSP framework, by introducing the characteristics of each scenario in a sector-relevant manner and offering opportunities for deeper exploration where interest arises (Wilbanks, Ebi, 2014).

Figure 6 – Fossil-Fueled Development (SSP5)



Source: own elaboration.

5. Final Considerations

The downscaled SSP framework therefore provides critical guidance for multilevel policymaking. It offers federal, state, and municipal actors' insight into the concentration of adaptation and mitigation efforts, the alignment of development pathways with current trends, and the need for stronger political and economic mobilization. Regional downscaling establishes a valuable analytical structure to examine how climate impacts and development choices interact across scales, particularly in the context of Brazilian agribusiness. It helps elucidate how trajectories, processes, and decisions at distinct levels are interrelated, shaping long-term sectoral outcomes. Advancing more integrated research approaches is essential if SSPs are to fulfill their potential in addressing policy-relevant questions—particularly regarding the range of climate impacts under different development pathways, and the extent to which adaptation and mitigation can reduce residual damages and associated costs. In addition, the framework underscores how divergent socioeconomic futures can influence both the feasibility and the distributional equity of climate responses across diverse categories of producers.

A significant contribution to this analysis is its capacity to support the development of indicators of adaptive capacity. These indicators can be used to monitor the implementation and effectiveness of adaptation policies over time, offering a practical tool to evaluate the progress toward climate-resilient agriculture. Furthermore, the framework emphasizes the necessity of customizing public interventions to suit the diverse profiles of producers. While large agribusinesses may require regulatory incentives and mitigation targets, small and medium producers need targeted support through credit access, extension services, and scalable, low-cost technologies.

Ultimately, integrating socioeconomic scenarios with sectoral and regional specificities is essential to build a resilient agricultural future in Brazil. The different challenges and opportunities presented by each SSP underscore the necessity of coordinated, inclusive and forward-looking governance mechanisms to navigate the risks of climate change while promoting sustainable development.

Downscaling Shared Socioeconomic Pathways (SSPs) to Brazilian agriculture promotes the applicability of global scenarios by generating regionally specific insights into vulnerabilities, adaptive capacities, and mitigation demands. Despite their global origin, SSPs offer a consistent framework for assessing plausible futures and informing policy decisions at multiple governance levels.

The comparative analysis of SSP1, SSP3, SSP4, and SSP5 reveals starkly divergent trajectories for climate resilience, productivity, and social equity. SSP1 emerges as the most sustainable and inclusive path, while SSP3 and SSP4 intensify regional disparities and limit adaptation among smallholders. SSP5 supports high productivity through technological innovation but at the cost of rising environmental risks, underscoring the importance of robust governance mechanisms.

These findings highlight the need for differentiated policy strategies tailored to regional and producer-specific realities. Downscaled SSPs can serve as a valuable planning tool to develop a resilient, equitable, and low-carbon agricultural development. Future research should expand this approach beyond agriculture to include interconnected sectors such as climate-adaptive genetics, rural mechanization, food systems, and dietary transitions.

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