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RESEARCH PAPER

A systems dynamics approach to climate change policies in soybean production and transportation in Brazil

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ABSTRACT

Goal: The growing demand for food and the need to reduce greenhouse gas (GHG) emissions require sustainable solutions in the agricultural sector, particularly in the transportation of commodities such as soybeans. This study evaluates the combined impact of transportation policies and sustainable agricultural practices on the soybean supply chain in Brazil, utilizing an Integrated Assessment Model (IAM) based on System Dynamics (SD).

Design/methodology/approach: The model simulates various public policy scenarios, including the National Logistics Plan (PNL35), alongside agricultural practices such as No-Tillage Systems (NTS) and the Legal Reserve Law (LRL).

Results: The results indicate that PNL35 has the potential to reduce CO2 emissions by up to 23%, albeit constrained by logistical costs. The expansion of NTS and LRL enhances carbon sequestration, offsetting a portion of transport emissions.

Limitations of the investigation: A limitation of this study is that it does not fully account for infrastructure constraints and dependence on external funding, which may pose significant financial and regulatory barriers to the practical implementation of the proposed strategies.

Practical implications: The study provides practical insights for policymakers and agribusiness managers by showing that integrating transport infrastructure planning with sustainable farming practices can significantly reduce Brazil's soybean supply chain emissions and support national decarbonization goals.

Originality/Value: The study underscores the importance of integrating transportation policies and sustainable agricultural practices to achieve decarbonization targets in the sector.

Keywords: Integrated assessment model; Sustainable agriculture; Decarbonization; No-tillage.

1 INTRODUCTION

Economic growth is fundamental to global development but is one of the primary drivers of adverse environmental impacts, such as air pollutant emissions and the unsustainable use of natural resources (Soener, 2019). In agriculture, practices like monocropping and industrialized farming have intensified pressure on critical resources, such as water, soil, and biodiversity, thereby compromising long-term food security and environmental sustainability (Hedayati et al., 2019; Godfray & Garnett, 2014).

In addition to the direct impacts of agricultural production, the transportation of agricultural goods plays a significant role in greenhouse gas (GHG) emissions. The transportation sector, vital to the global economy, faces considerable challenges in addressing climate change mitigation. In

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2019, it was the second-largest global emitter of GHGs, comparable to industrial emissions (Transport and Climate Change Global Status Report, 2022). CO2 emissions associated with freight transportation are influenced by energy consumption per ton transported and infrastructure adequacy. In this context, decarbonizing the sector is a priority, especially in countries like Brazil, which rely heavily on road transportation.

Given the economic importance of transportation and its contribution to climate change, it is crucial to analyze the vulnerability of the agricultural sector to these transformations. Agriculture, highly dependent on favorable climatic conditions, is particularly sensitive to shifts in climate patterns (Jensen et al., 2019). This vulnerability is exacerbated by reliance on regular precipitation, increasing production risks in scenarios of climate variability (Allegretti et al., 2018). Thus, implementing mitigation and adaptation strategies in the agricultural sector is critical to ensuring food security and sustainability.

Developing countries like Brazil face additional challenges, including rising average temperatures, more frequent extreme weather events, and an economy heavily reliant on the agro-industrial sector, which is highly sensitive to climate change (Pradhan & Ghosh, 2019). From this perspective, logistics plays a strategic role in agricultural efficiency and profitability, particularly in regions with inadequate infrastructure, where efficient transportation capacity is essential for productivity and market access.

Given the urgency of promoting decarbonization and mitigating the impacts of climate change, this study investigates the adoption of sustainable policies and practices in the production and transportation of soybeans in Brazil. The approach involves constructing an Integrated Assessment Model (IAM) grounded in System Dynamics (SD), integrating climatic and economic variables in a manner akin to Nordhaus's DICE model (2018; 2023).

Despite the growing body of literature on low-carbon agriculture and on transport decarbonization, these domains are still predominantly analyzed in isolation. Existing studies typically assess either agricultural mitigation strategies focusing on land-use management and conservation practices (Cheng et. al 2023; Momm et al. 2024; Lu et. al 2024; Thapa et al. 2025; Kim et al. 2025) or transportation decarbonization interventions centered on modal shift and fuel substitution (Sims et. al 2014; McKinnon, 2018; Wang et. al 2024). Although some supply-chain assessments exist, they rarely capture integrated economic and environmental feedbacks between production and logistics systems along global commodity flows (Poore; Nemecek, 2018). Given the urgency of promoting decarbonization and mitigating climate impacts in Brazil's export-oriented soybean sector, this study investigates the adoption of sustainable policies and practices in both production and transportation within a unified analytical framework.

IAMs have been widely applied to analyze the impacts of climate change on specific economic sectors, providing a comprehensive view of socio-economic and environmental variables (Weyant, 2017). Their application in sectors such as agriculture enables the formulation of adaptive policies aimed at mitigating climate impacts while maximizing economic efficiency (Popp et al., 2021). Studies conducted in the United States and Europe demonstrate that integrating sustainable agricultural practices with carbon pricing policies can simultaneously optimize productivity and reduce carbon emissions (Frank et al., 2021).

The goal of this study is to evaluate, within a unified dynamic framework, how transportation policies (modal sharing under PNL35) and agricultural sustainability instruments (No-Tillage Systems (NTS) and the Legal Reserve Law (LRL)) interact to shape logistics costs, modal allocation, land-use constraints, and greenhouse gas emissions along Brazil's soybean export chain. These aspects are analyzed from economic, logistical, and environmental perspectives to support the formulation of public policies aimed at sector sustainability. Building on integrated assessment theory (Weyant, 2017; Popp et al., 2021) and on the literature on low-carbon logistics and conservation agriculture, this study formulates the following hypotheses to structure empirical evaluation and theoretical contribution:

H1 – Modal Diversification Hypothesis: Increasing the share of lower-carbon modes (rail and waterways) relative to road transport reduces CO_2 emissions per unit of exported output, consistent with energy-intensity and modal efficiency theory (Dekker et al., 2012; Faria et al., 2024).

H2 – Agricultural Mitigation Hypothesis: The adoption of sustainable agricultural practices—specifically No-Tillage Systems (NTS) and compliance with the Legal Reserve Law (LRL)—reduces net emissions through enhanced soil carbon sequestration and lower fossil-fuel use without compromising long-term production, as predicted by conservation agriculture and land-use change theory (Hogarth, 2017; Maia et al., 2022).

H3 – Policy Complementarity Hypothesis: The joint implementation of logistics policies (PNL35) and agricultural sustainability instruments (NTS and LRL) produces synergistic emission reductions that exceed the effects of isolated interventions, consistent with integrated assessment and socio-technical transition frameworks emphasizing cross-sector complementarities (Siebers et al., 2020; Popp et al., 2021).

H4 – Cost–Emission Trade-off Hypothesis: Integrated policy packages dominate isolated measures in long-term cost–emission performance, revealing structural trade-offs between infrastructure investment, logistics efficiency, and climate mitigation that can be systematically evaluated within a dynamic IAM–SD framework.

These hypotheses provide a testable structure linking transportation diversification, agricultural practices, and emissions, enabling a theory-informed assessment of policy integration along Brazil's soybean export chain.

PNL35 was selected due to its relevance in diversifying the transportation matrix, promoting more sustainable modes such as rail and waterways. This strategy is crucial to reducing CO2 emissions associated with road transport, which predominates in the flow of agricultural commodities in Brazil (EPL, 2021). Additionally, the ABC+ Program plays a strategic role in promoting low-carbon agricultural practices, such as NTS and the recovery of degraded pastures, aligning with Brazil's commitments under the Paris Agreement (MAPA, 2023). Finally, the LRL reinforces biodiversity preservation and carbon sequestration, representing an essential measure in the context of agricultural expansion.

In this study, these initiatives provide an integrated approach to addressing the climatic and economic challenges of Brazil's agricultural and logistics sectors, considering sustainability aspects and meeting decarbonization targets.

2 SYSTEM DYNAMICS AND THE DICE INTEGRATED ASSESSMENT MODEL

System dynamics (SD) models offer a robust framework for investigating the complex interactions between climate dynamics and the economy, enabling the analysis of extreme events and their socioeconomic implications (Forrester, 1985). One of the primary advantages of this approach is its ability to explicitly represent feedback relationships, temporal delays, and non-linearities intrinsic to complex systems, making it a valuable tool for simulating and evaluating climate change mitigation and adaptation policies (Li et al., 2012; Blaint et al., 2017).

SD models excel in naturally integrating features such as non-linear dynamics, various time scales, and feedback loops. These models analyze systems out of equilibrium using aggregate equations that capture the overall system evolution without detailing individual agent heterogeneity or interactions (Blaint et al., 2017). Comparatively, their relatively simplified macroeconomic structure makes them more accessible for statistical calibration and practical application.

The first notable application of an SD model in the context of sustainable development was the WORLD3 model, developed for the Limits to Growth report (Meadows et al., 1972; Blaint et al., 2017). This report highlighted the risks of uncontrolled growth patterns, which could lead to global collapse. Later, the climate dimension was incorporated into the model by Fiddaman (1997), marking one of the earliest attempts to use SD for integrated assessment of complex economic and climate structures (Blaint et al., 2017).

A distinctive feature of SD models is their ability to visually represent the structure of complex systems through causal loop diagrams and stock-and-flow diagrams. These representations make explicit the cause-and-effect relationships and feedback mechanisms present in the analyzed systems (Ding et al., 2018). The SD approach is based on constructing systems of differential equations that describe the temporal evolution of system state variables, rates, and flows (Forrester, 1985). Computational tools such as Stella®, Vensim®, and Powersim® facilitate the construction, simulation, and analysis of these models.

SD has proven to be a valuable tool for analyzing the complexity of agricultural systems and aiding in the formulation of effective public policies for the sector. This approach allows for the modeling of interactions among different system components—economic, social, environmental, and political—and simulates the impact of various scenarios and interventions. Numerous studies have demonstrated the applicability of SD in diverse agricultural contexts.

For example, Wang et al. (2022) used system dynamics to simulate the impact of policies on green agricultural development in the Tibetan area of Sichuan, China. The authors concluded that targeted policies focusing on the harmony between economy, society, and ecology are crucial for achieving sustainable agricultural development. In the Brazilian context, Martins et al. (2024) employed SD to analyze the sustainability of agribusiness expansion in the MATOPIBA region (an acronym for the Brazilian states of Maranhão, Tocantins, Piauí, and Bahia), emphasizing the importance of integrating water, energy, and socioeconomic dimensions in public policy analysis for the sector. Another example is the study by Vaccaro et al. (2018), which analyzed the ethanol production chain in southern Brazil, focusing on associative production and family farming. Using system dynamics modeling, the authors mapped the variables and interrelationships among actors in the production chain, concluding that understanding these interactions is critical to developing actions that promote the sector's sustainability and competitiveness.

Within this context of models that integrate different dimensions to analyze complex systems, the DICE model (Dynamic Integrated Climate-Economy model) stands out. Although not originally conceived as an SD model, it shares several characteristics typical of this approach. DICE enables long-term projections of the climate-economy system by analyzing different climate policy scenarios and their respective impacts (Kellett et al., 2019). It incorporates non-linear processes, such as the amplified effects of temperature increases on the economy, which intensify climate change impacts over time (Nordhaus, 2018).

3 METHODOLOGICAL PROCEDURES

This section outlines the methodological procedures adopted in the research, detailing the steps taken for model construction, data collection and analysis, and scenario simulation. Initially, the study area will be described, providing context on the region and the research object. Next, the methods and techniques used for model development, data collection, and result analysis will be presented. Finally, the simulation stages and scenarios analyzed will be detailed.

3.1. Study Area

The soybean complex exemplifies the dynamics of commodity cycles, characterized by seasonal supply driven by favorable climatic conditions. With exports projected to reach 96.5 million tons for 2023/24, Brazil is set to consolidate its position as the world's largest supplier, accounting for 56% of the global soybean market. Alongside the United States, which ranks second, Brazil represents over 90% of global soybean trade (USDA, 2023). The expansion of Brazilian production occurs primarily through pasture conversion, crop substitution, and advancement into new agricultural frontiers (MAPA, 2019).

The soybean sector plays a central role in Brazil's economy, significantly contributing to GDP and technological advances in agribusiness. Studies indicate that soybean productivity has been a driver of national economic growth, promoting efficient land use and boosting competitiveness in the international commodities market (Ferreira Filho & Horridge, 2016; Martha Jr. et al., 2012). This dependence is reflected in Brazil's economic structure, where agribusiness remains crucial for job creation and economic growth (Sauer & Leite, 2012).

Despite advancements in productivity and the expansion of cultivated areas, soybean profitability in Brazil depends on favorable climatic conditions and efficient logistics for transporting production. The Brazilian logistics matrix is predominantly road-based, known for its high operational costs and pollutant emissions (Dekker et al., 2012). During harvest seasons, road freight costs can exceed 30% of the grain's value, undermining producers' competitiveness (IMEA, 2017).

Soybean exports are concentrated during the harvest months (March to May), accounting for approximately 50% of the annual total. This seasonal peak overloads port infrastructure and drives up transportation costs due to increased demand, leading to higher freight rates and reduced port premiums, which are adjusted to balance export flow (CONAB, 2017).

Deficient infrastructure is one of the main logistical bottlenecks, reducing Brazil's competitiveness in the international market (Peine, 2020). While recent efforts have aimed to increase private investment in the sector, significant gaps remain in implementing efficient solutions for grain transportation and distribution.

From an environmental perspective, the dominance of road transport exacerbates CO2 emissions, placing Brazil at a disadvantage in adopting eco-efficient routes. These routes, which balance logistical costs and emissions, face challenges such as inadequate intermodal infrastructure, unfavorable locations of transshipment points, and high logistical costs (Zaluski, 2018). Intermodal transport is hindered by factors such as long distances and high variable costs, limiting the potential for emission reductions and promoting greater dependence on road transport.

3.2. SD Model Construction

The model was developed based on the systematic organization and analysis of real historical data on soybean production and export, covering the period from 2006 to 2035. Validation metric results, including R^2, MAPE, MAD, and RMSE, are presented in Table 1. An R^2 value close to 100% indicates a strong agreement between the simulated data and observed real-world behavior.

Low MAPE values further reinforce the accuracy of the forecast model. However, the MAD and RMSE values highlight the presence of some significant deviations between simulated and actual values. Nevertheless, these deviations do not compromise the model's overall reliability, which demonstrates high global accuracy.

Table 1 - Adjustment metrics between data series and simulated results

	R^2	MAPE	MAD	RMSE
Export	88.7%	12.56%	490793.39	595967.85
Production	91.5%	5.28%	440290.90	626913.98

Although R^2 and MAPE indicate strong overall fit, the magnitude of MAD and RMSE reveals localized deviations between simulated and observed series, particularly during periods of high volatility and harvest-season peaks. These deviations suggest that short-term dynamics and extreme values may be smoothed by the aggregated structure of the SD model. Accordingly, the model is best suited for comparative scenario analysis and long-term structural assessment rather than for short-term point forecasting. Thus, the results should be interpreted in terms of relative differences across scenarios and persistent trends, not as exact year-by-year predictions.

To explicitly address parameter uncertainty, a global sensitivity analysis was conducted using Latin Hypercube Sampling with 50 simulations (McKay et al., 1979), as detailed in the Supplementary Material. The parameters tested include price effects on demand, delays in price transmission, reference prices, growth rates of demand, exports, and production, investment fractions, and the modal shares of road, rail, and waterways. The results indicate that model outputs are particularly sensitive to variations in the transportation matrix, demand and export growth rates, and reference prices, whereas investment-related parameters and domestic price adjustments exert comparatively smaller effects. This finding indicates that system behavior is primarily driven by the structural configuration of logistics and market expansion dynamics rather than by short-term financial adjustments, thereby increasing transparency regarding the dependence of results on underlying assumptions.

Consistent with this assessment, the interpretation of model outputs accounts for parameter uncertainty. Although the sensitivity analysis reveals dispersion in outcome magnitudes, particularly for CO2 emissions and export volumes, the direction of change and the relative ranking of scenarios are preserved across all simulations. In contrast, logistics costs and domestic demand exhibit narrower confidence bands, indicating greater structural stability. This pattern suggests that, while absolute values are sensitive to plausible parameter variation, the comparative insights derived from the model reflect structural properties of the SD–IAM framework rather than specific parameter choices. Accordingly, the model is best suited for comparative scenario analysis and long-term policy assessment, rather than short-term point forecasting.

3.2.1. Production and Storage Modeling

The production and storage modeling was structured to represent the dynamics of grain production, storage, and distribution throughout the simulation period.

The production flow was based on a historical growth rate function, projecting annual production behavior. Storage dynamics were modeled using the *conveyor concept* available in the Stella Architect© software, enabling precise representation of grain accumulation and outflow over time while accounting for the seasonality of the production cycle.

The main stock, labeled "Harvest/Period," receives the produced grains and allocates them to various consumption destinations. This process is described by a differential equation that incorporates production flow, supply flow, and adjustment times. Storage is divided between industrial processing for domestic consumption and grain storage for export, integrating variables such as industry acquisition rates and domestic and external market consumption rates. These variables are adjusted according to demand trends and market prices, creating a dynamic and adaptive representation of the system.

The structuring of these stocks and flows was essential to reflect the interactions between supply, demand, and storage, highlighting the interdependence between different markets and the economic and logistical impacts on the supply chain. Figure 1 provides a graphical representation of the stock-and-flow diagram for production, storage and dynamics of domestic consumption and export.

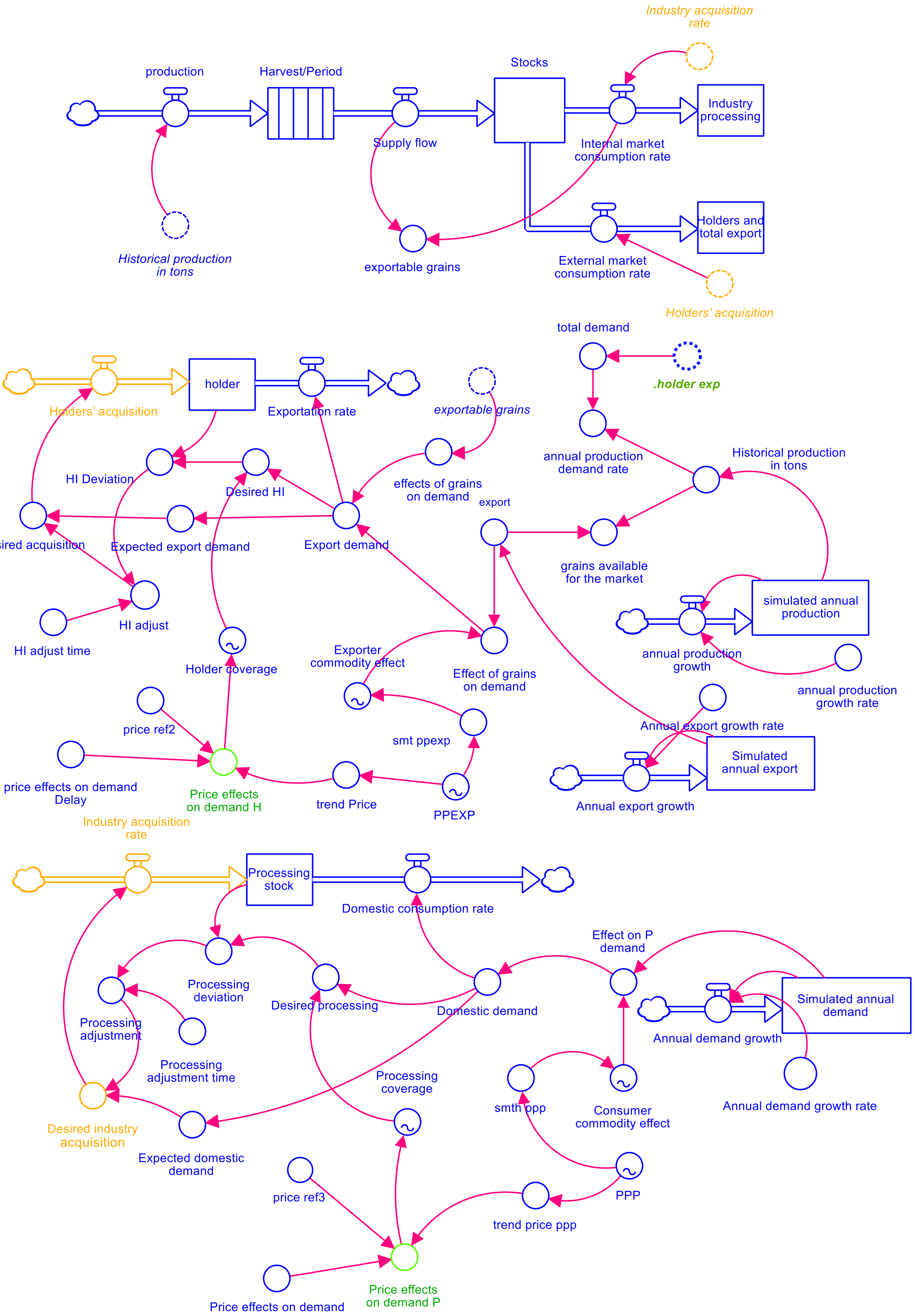

Figure 1 - Production, Gross Storage and Dynamics of Domestic Consumption and Export

3.2.2. Dynamics of Domestic Consumption and Export

The dynamics of domestic consumption and export were modeled by considering the interactions between internal and external markets, both influenced by the "commodity effect," which adjusts consumption rates based on prevailing prices. The domestic market is directly impacted by the Producer Purchase Price (PPP), where lower price attractiveness in the external market tends to retain grains in the domestic market, increasing local supply. Conversely, the external market is driven by the Exporter Purchase Price (PPEXP), where an increase in international prices generates a positive reinforcement in grain demand by exporting holders.

These behaviors were simulated using differential equations that link acquisition and consumption flows to available stock levels. Additionally, a competitive system between markets was incorporated, influenced by government policies, such as the use of parity pricing to balance internal competitiveness. Parameters for modeling consumption rates, PPP, PPEXP, and price effects on demand were based on historical data series from CONAB (2023) and fine-tuned using graphical functions constructed in Stella Architect© software.

For each market, consumption rate variables and stock coverage were adjusted according to future price and demand trends, resulting in a dynamic model responsive to changes in economic conditions. This approach enabled an analysis of how grain allocation decisions between domestic and external markets impact stocks and flows over the simulation period (Figure 1).

3.2.3. Modal Distribution and Emissions

The modeling of modal distribution and emissions was designed to capture the dynamics of grain transportation between production regions and their destination markets, considering different transportation modes (road, rail, and waterway). Fuel consumption data and mileage were used to calculate equivalent CO2 emissions, following the IPCC (2013) methodology and technical parameters specific to each transportation mode. The current Brazilian modal matrix was used as a reference, with 63.3% of freight transported by road, 21.7% by rail, and 14.9% by waterways, according to EPE (2022).

Total route mileage was determined through geoprocessing in Quantum GIS (QGIS®) software for rail and waterway modes and via Google Maps for road transportation. Emissions were calculated based on diesel consumption per thousand ton-kilometer (TKU): 15 L/1,000 TKU for roads, 9.29 L/1,000 TKU for rail, and 4 L/1,000 TKU for waterways (ANTT, 2014a; IPEA, 2014). The diesel emission factor adopted was 2.603 kgCO2/L (IPCC, 2013). Emission flows were modeled in Stella Architect© software using array properties to differentiate emissions by mode.

Additionally, the model accounted for the impact of intermodal shifts projected by the National Logistics Plan (PNL35), which forecasts a gradual reduction in road dependency to 32% by 2035, with increased participation of rail and waterway modes (EPL, 2021).

The total emissions calculation was integrated with economic variables to evaluate transportation costs and net emissions per ton of transported grain. This approach enabled an analysis of the potential for emission reductions and the associated costs of adopting a more sustainable logistics matrix, demonstrating the environmental and economic impacts of modal diversification policies (Figure 2).

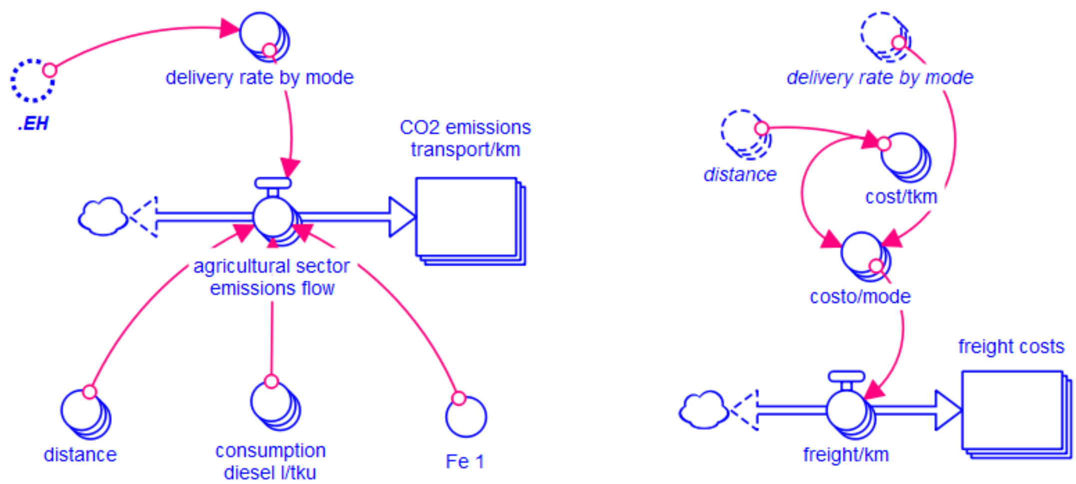

Figure 2 - Modal Distribution and Emissions Diagram

3.2.4. Integration of Climate and Economy – Dynamic Integrated Climate-Economy Model

The integration of economic and climate models was conducted to evaluate the impacts of logistical choices and decarbonization policies on the economy and climate using the Dynamic Integrated Climate-Economy (DICE) model, developed by Nordhaus (1994, 2018). The economic model is based on a Cobb-Douglas production function, incorporating capital elasticity, total factor productivity (TFP), and capital stock as primary variables. The climate variables include atmospheric CO2 stock, radiative forcing, and temperature changes. Input data for the climate module were calibrated based on global parameters from the DICE-2023 model, including atmospheric retention rate (0.64), radiative forcing coefficient (4.1 W/m²), and the deep ocean thermal capacity ratio (0.44) (Barrage & Nordhaus, 2024).

Emissions from multimodal grain transportation were integrated into the total agricultural sector emissions and global CO2 levels, calculated using data from CONAB (2023) and modal-specific diesel consumption and emission parameters established by ANTT (2014a) and IPCC (2013). The impact of emissions on the climate was modeled considering radiative forcing and the ocean's absorption capacity, while economic damages were calculated as a fraction of GDP using the DICE climate damage fraction function (Nordhaus, 2018).

The economic dynamics incorporated variables such as capital investment, depreciation, carbon intensity, and TFP growth. For Brazil, TFP was conservatively assumed to be 0.01, based on projections from the World Bank (2023) and IBRE (2024). Additionally, the costs and benefits associated with the transition to sustainable agricultural practices, such as No-Tillage Systems (NTS), and modal diversification in transportation were included. This integration enabled the assessment of the economic and climatic impacts of proposed policies by simulating various emission reduction scenarios and mitigation strategies over the 2006–2035 period. Figure 3 contains the diagram of carbon cycle, climate, carbon intensity and economic modules.

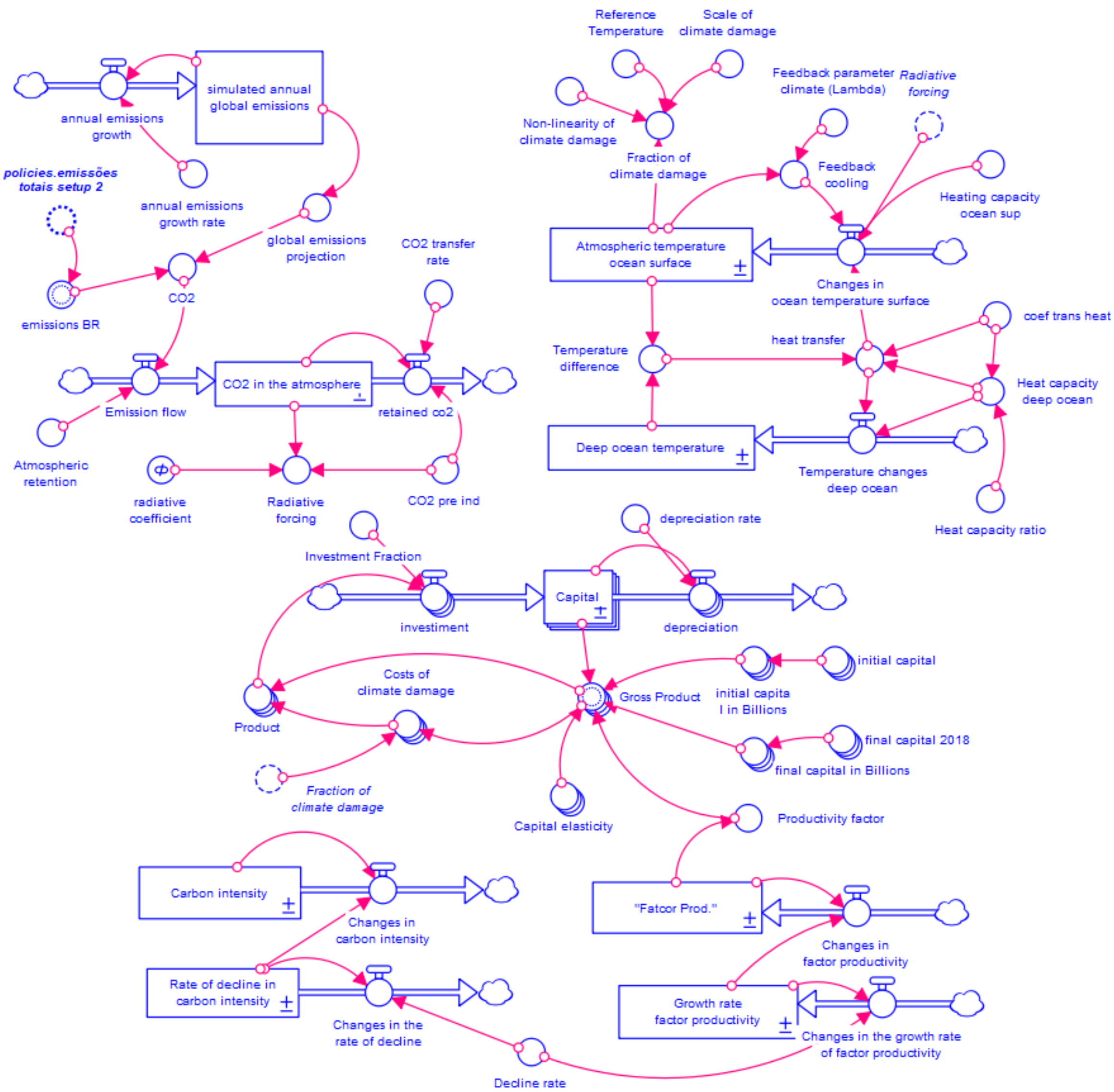

Figure 3 - Diagram of Carbon Cycle, Climate, Carbon Intensity and Economic Modules

3.2.5. Policies and evaluated scenarios

The policies and scenarios evaluated were structured to measure the impacts of decarbonization strategies in the soybean logistics chain, combining modal diversification with sustainable agricultural practices. Key modeled policies include the transition to NTS, compliance with the LRL, and the implementation of the National Logistics Plan 2035 (PNL35). Emission reduction and cost projections were simulated considering baseline and incentivized policy scenarios.

The adoption of NTS, as outlined in the ABC+ Plan, was modeled based on an average cultivated area expansion rate of 14.59 million hectares between 2010 and 2019 (MAPA, 2023). This system was combined with the carbon sequestration potential of legal reserve areas, using sequestration factors ranging from 0.4 to 8.6 Gt CO_2 per year (IPCC, 2013). For cost-benefit calculations, the production costs per hectare for NTS (R$ 3,557.70) and conventional systems (R$ 4,901.81) were derived from EMBRAPA (2019).

The Bass diffusion model (1969) was employed to analyze the adoption of sustainable management practices over the 2006–2035 period (Figure 4). Historical data series on total cultivated area from 1976 to 2022 were analyzed to project and simulate growth up to 2035.

The adoption curve generated by the model displayed a typical "S-shaped" behavior, with an initial slow growth phase driven by innovators, followed by an accelerated phase as imitators increase the adoption rate, and eventually stabilization as the system approaches saturation. For simulation purposes, Brazil's arable land limit of 65.9 million hectares (World Bank, 2023) and the expected proportion of cultivated areas under NTS were considered.

In the context of PNL35, modal diversification was projected to gradually reduce road transport dependency (63.3%) to 32%, while increasing rail (47%) and waterway (19%) participation by 2035 (EPE, 2022; EPL, 2021). Scenarios were structured into three progressive phases of intermodality, evaluating both emission reductions and associated logistics costs. Emission rates per modal were calculated using diesel consumption factors per TKU provided by ANTT (2014a) and IPEA (2014), while transportation costs were sourced from PNLP (2015) and ANTT (2013).

Uncertainty was explicitly addressed in key structural parameters of the model. Adoption rates of NTS, land availability constraints, and emission factors were derived from historical series and the literature, but their future evolution remains subject to economic, institutional, and climatic variability. To account for this, these parameters were defined as ranges rather than point estimates and tested through sensitivity analysis. This approach enables the identification of robust system behaviors under plausible parameter variation and increases transparency regarding the dependence of results on underlying assumptions.

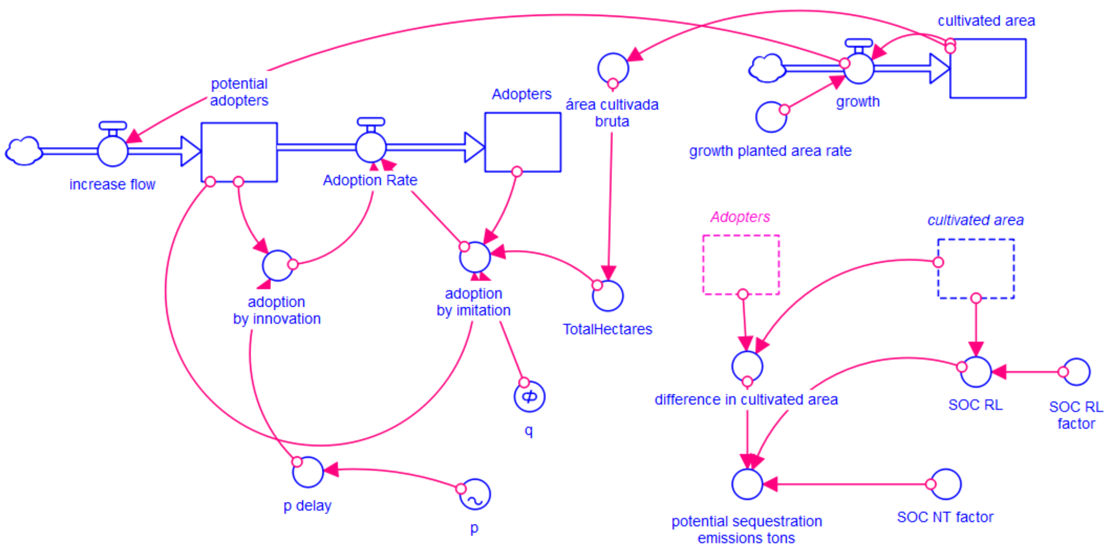

Figure 4 - Bass Diffusion Model Diagram for No-Tillage System (NTS) + Legal Reserve

4 RESULTS AND DISCUSSION

This section presents the simulation outcomes in direct relation to the hypotheses formulated in the Introduction. Specifically, we evaluate: (i) the effect of modal sharing on emissions (H1); (ii) the mitigation potential of sustainable agricultural practices (H2); (iii) the presence of synergistic effects from the joint implementation of logistics and agricultural policies (H3); and (iv) the long-term cost–emission trade-offs associated with integrated policy packages (H4).

The PNL35 aims to transform Brazil's transportation matrix by enhancing efficiency, safety, and sustainability, as well as reducing logistics costs for freight and passenger movement and decreasing environmental gas emissions (EPL, 2021). Table 2 provides the parameters used for the baseline scenario and projections for each stage in the modal sharing proposed by PNL35.

Table 2 - Baseline Scenario and Projections for 2035 (%)

Modals	Baseline	Phase 1	Phase 2	Phase 3
Road	63.3	55	40	32
Rail	21.7	31	43	47
Waterway	14.9	13	16	19

Source: EPE (2022); EPL and IMEA (2021).

Figure 5 presents the simulation results of four distinct scenarios, focusing on the impacts of PNL35 and NTS on the soybean production and transportation chain. Graphs A and B illustrate the CO2 emission projections and the primary costs associated with the intermodalization of transportation, respectively, under the three scenarios proposed by PNL35. Graph C highlights the net emissions from the soybean supply chain, considering carbon sequestration (SOC) and the gradual replacement of transportation modes. Graph D shows the total production and transportation costs under the incentivized adoption of NTS. These results provide a comprehensive view of the environmental and economic implications of combining sustainable transportation policies with agricultural practices.

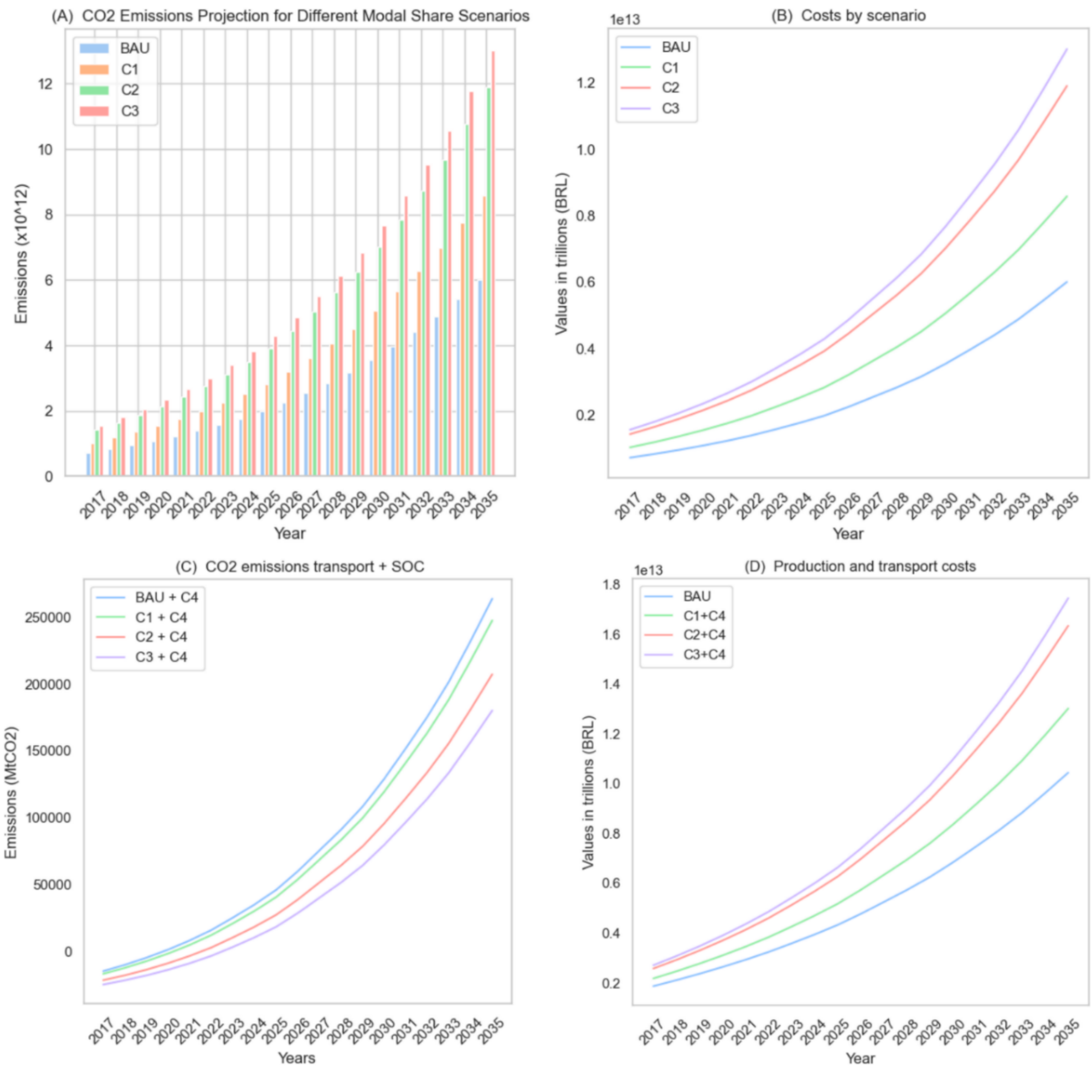

Figure 5 - Dynamic Model Results

(A) CO_2 emissions per scenario in grain transportation. **(B)** Transportation costs per scenario: Gradual substitution of road, rail, and waterway transportation modes as proposed by PNL35. **(C)** Net emissions from the soybean supply chain (carbon sequestration (SOC) + gradual substitution of transportation modes). **(D)** Production and transportation costs of soybeans under the incentivized adoption of the NTS system.

The scenarios C1, C2, and C3 represent projections for transportation modal sharing proposed by PNL35. In scenario C1, most freight transportation remains road-based, keeping CO_2 emissions high due to intensive truck usage. Scenario C2 predicts an increase in the use of more sustainable modes, such as railways and waterways, supported by investments and incentives targeted at companies adopting low-carbon technologies. In scenario C3, railway transport predominates, significantly reducing road dependency. These results provide direct support for Hypothesis H1. As the participation of rail and waterways increases under PNL35 (from C1 to C3), CO_2 emissions per transported output decline monotonically, confirming that modal sharing toward lower-carbon modes leads to significant emission reductions relative to a road-dominant baseline.

Table 3 - Emission Reduction Percentage by Scenario (PNL35)

PNL35 Modal Sharing Scenario	CO_2 Reduction Percentage
C1: Road 55%; Rail 31%; Waterway 13%	4.65%
C2: Road 40%; Rail 43%; Waterway 16%	16.16%
C3: Road 32%; Rail 47%; Waterway 19%	23.89%

The magnitude of the reductions, reaching 23.89% in scenario C3, empirically validates H1 within the modeled export corridors, demonstrating that decarbonization gains are structurally linked to shifts in modal allocation rather than marginal efficiency improvements within road transport.

Nevertheless, these environmental gains are not cost-neutral. Modal shifts toward rail and waterways require substantial upfront investments in infrastructure, terminals, and network integration. While the model captures higher fixed costs associated with rail transport (Faria et al., 2024), it also indicates that short-term logistics costs may increase before emission benefits fully materialize. This trade-off highlights a critical policy tension: the timing of infrastructure expenditures versus the long-term social value of emission reductions. In practice, the feasibility of large-scale intermodality depends on access to long-term financing, regulatory coordination, and the capacity of public–private partnerships to absorb initial capital costs.

In comparative terms, the magnitude of emission reductions observed in the integrated scenarios is consistent with international empirical evidence and policy benchmarks. In the European Union, comparative assessments of freight transport consistently show that road transport exhibits substantially higher greenhouse gas emissions per tonne-kilometre than rail and inland waterways, implying significant mitigation potential from modal shifts along long-distance corridors (European Environment Agency, 2022). Reflecting this evidence, European transport policy explicitly targets a modal transfer of at least 30% of road freight over distances above 300 km to rail or waterborne transport by 2030, a transition associated with corridor-level emission reductions typically ranging from 15% to 30%, depending on baseline modal shares and infrastructure constraints (European Commission, 2011; ITF, 2021). From an agricultural perspective, international studies on conservation agriculture demonstrate that no-tillage systems and reduced soil disturbance are associated with net gains in soil organic carbon over medium- to long-term horizons, particularly when evaluated over deeper soil profiles and appropriate temporal scales (Poeplau & Don, 2015; Paustian et al., 2016). Although the magnitude of sequestration remains context-dependent and influenced by climate, soil type, and management intensity, the convergence between these international findings and the results of the present model strengthens the external validity of the analysis. At the same time, the comparison underscores Brazil-specific challenges, such as regional heterogeneity in infrastructure availability, institutional coordination, and access to financing, that may condition the pace and scale at which similar mitigation outcomes can be realized in export-oriented agri-logistics systems.

In Brazil, freight transportation infrastructure is one of the main limitations to multimodal efficiency, characterized by an excessive reliance on road transport. This mode, besides being more expensive, contributes to slower logistical processes exacerbated by the lack of integration points between modes. Rail transport, for instance, incurs high fixed costs regardless of the transported volume. While rail transport is less polluting than road transport, its lack of route flexibility is a significant limitation (Faria et al., 2024).

When considering long-term policies, the BAU (Business-As-Usual) reference scenario combined with the incentivized No-Tillage System (NTS) policy (C4) demonstrates the best balance between performance, costs, and emissions compared to other scenarios. In Brazil, environmental policies for agribusiness aim to balance the sector's economic development with environmental sustainability. These policies encourage ecologically sound practices, focusing on mitigating negative externalities related to land use and biodiversity preservation (MAPA, 2020).

NTS, introduced more than two decades ago, stands out as an effective mitigation strategy by reducing mechanization intensity and enhancing soil carbon sequestration (Maia et al., 2022; Hogarth, 2017). As the second-largest country in cultivated area under NTS, Brazil concentrates approximately 18% of the global adoption of this practice (Maia et al., 2022). The results confirm Hypothesis H2: the expansion of NTS and compliance with the LRL reduce upstream emissions through increased soil organic carbon (SOC) and lower fossil fuel use, while preserving long-term production levels. This indicates that agricultural mitigation can decouple emissions from export growth, reinforcing the role of land-use management as a structural driver of low-carbon supply chains.

The results obtained indicate that sustainable land-use strategies and efficient agricultural practices can play a decisive role in reducing total emissions from the soybean transportation chain. In the simulated scenario with greater adoption of practices such as no-till farming and crop-livestock-forest integration, a reduction of up to 23% in total CO2 emissions was observed, even with increasing transportation demand. This finding is consistent with empirical evidence showing how land use and land cover types directly influence carbon stability and CO2 fluxes. In a recent study conducted in the Cerrado biome, Silva et al. (2024) observed that silvopastoral systems exhibited a higher capacity for soil carbon retention and stabilization when compared to areas converted to planted forests, such as eucalyptus plantations. The greater accumulation of organic matter and increased cation exchange capacity at depth were identified as key factors for lower soil respiration and, consequently, reduced CO2 emissions.

Thus, H2 is supported: sustainable land-use and management practices deliver measurable mitigation benefits without compromising the functional performance of the soybean export chain.

Importantly, the combined scenario (integrating PNL35 with NTS and LRL) produces emission reductions that exceed those obtained by implementing transportation or agricultural measures in isolation. This outcome is consistent with the literature on integrated assessment and socio-technical transitions, which emphasizes complementarities between land-use management and transport decarbonization (Siebers et al., 2020; Popp et al., 2021). Similar synergistic effects have been reported in empirical studies of climate-smart agricultural systems and intermodal logistics planning (Bieluczyk et al., 2024; Faria et al., 2024), reinforcing the external validity of the model's structural behavior.

The model reveals that these synergies emerge from feedback mechanisms between modal diversification, reduced carbon intensity per ton-kilometer, and increased soil carbon stocks, which cannot be captured through sector-specific analyses.

Despite the robustness of the results, they remain contingent on key modeling assumptions. Adoption dynamics of NTS and intermodality are represented through diffusion functions calibrated on historical trends, which may not fully capture institutional barriers, heterogeneous producer behavior, or strategic responses to policy incentives. Emission factors and cost parameters are derived from secondary sources and may vary regionally, introducing additional uncertainty in absolute estimates. Moreover, the aggregated structure of the SD model limits the representation of spatial heterogeneity across corridors and producer types. These limitations do not invalidate the comparative insights, but they indicate that the findings should be interpreted as structural tendencies rather than precise forecasts, reinforcing the need for complementary empirical and spatially explicit analyses in future research.

4.1. Policy implications

The findings of this research provide valuable insights into decarbonization strategies for Brazil's transportation and agricultural sectors, with a focus on the National Logistics Plan 2035 (PNL35) and the ABC+ Program. Both initiatives are critical for reducing greenhouse gas (GHG) emissions in strategic sectors, aligning with national climate goals and fostering sustainable growth.

While the modeled results indicate substantial emission reductions from modal diversification and the adoption of NTS, their real-world implementation depends on a set of enabling conditions that are only partially captured in aggregate modeling exercises. In the case of transportation, the effectiveness of PNL35-type strategies is conditional on the availability of long-term infrastructure financing, the sequencing of investments in terminals and intermodal nodes, and regulatory coordination across federal, state, and private actors. Without these institutional arrangements, modal shifts may remain confined to a limited set of corridors, delaying the realization of emission benefits despite favorable cost–emission ratios at the system level.

In agriculture, although NTS and related low-carbon practices are cost-efficient over the medium and long term, their diffusion is strongly mediated by access to rural credit, technical assistance, and risk-sharing mechanisms, particularly for small and medium producers. This implies that policy outcomes simulated under full or accelerated adoption scenarios should be interpreted as conditional potentials, rather than automatic outcomes. Bridging the gap between modeled efficiency and effective implementation therefore requires complementary financial instruments, extension services, and institutional capacity-building to reduce adoption frictions and align private decision-making with long-term decarbonization objectives.

Despite the modeled efficiency of both NTS and modal diversification, their diffusion is frequently constrained by socio-economic and institutional barriers. In agriculture, empirical evidence from Brazil's low-carbon agriculture policy context indicates that limited access to rural credit and uneven availability of technical assistance/extension can materially slow adoption, particularly among small and medium producers, by increasing perceived risk and constraining investment capacity (Newton et al., 2016; Embrapa, 2021). In logistics, the implementation of intermodal solutions is often impeded by coordination failures across actors, regulatory complexity, and persistent regional inequality in infrastructure provision, which collectively raise transaction costs and reduce the reliability advantages needed for modal shift to occur at scale (ITF, 2019; World Bank, 2022; Ferreira; Marques, 2022). These constraints imply that emission-efficient trajectories identified by the model may face non-trivial transitional frictions, reinforcing the importance of complementary financial instruments, institutional coordination, and capacity-building policies to unlock adoption and translate modeled potentials into realized decarbonization outcomes (Newton et al., 2016; ITF, 2019).

PNL35 aims to restructure Brazil's commodity transportation matrix, promoting a shift from the road-dominated and emission-intensive transport mode to rail and waterways. This transition could reduce GHG emissions associated with soybean transport by up to 30%, representing significant progress toward long-term climate goals. These advances, however, depend on effective institutional and financial instruments that enable sustainable investments throughout the logistical and productive chain. As highlighted by Jiang et al. (2025), green finance plays a crucial role in overcoming financing barriers, driving the implementation of clean technologies, and amplifying the impact of decarbonization policies on CO2 emissions.

The plan's execution depends on substantial infrastructure investments, particularly in regions with limited access to sustainable transport modes. Public-private partnerships (PPPs) play a vital role in enabling projects that face financial and regulatory challenges (KPMG, 2023; World Bank, 2023).

In agriculture, the ABC+ Program is central to the sector's decarbonization. By promoting practices such as No-Tillage Systems (NTS) and the recovery of degraded pastures, the program aims to restore 30 million hectares of pastures and expand NTS to 12.5 million hectares by 2030.

These actions have significant potential to mitigate agricultural emissions and increase productivity. However, socioeconomic barriers, such as limited access to rural credit and inadequate technical support, hinder widespread adoption. Public policies targeting small and medium-scale farmers are essential to maximize the program's benefits (USDA, 2021; WRI, 2023).

The research also highlights Brazil's potential in the global carbon market, driven by the adoption of sustainable agricultural practices. Initiatives like ABC+ could generate carbon credits meeting up to 22% of the projected global demand by 2030. However, this opportunity requires a robust regulatory framework to ensure transparency and environmental integrity in credit trading. Encouraging smallholder participation in this market is crucial to amplify social and environmental benefits while strengthening economic inclusion (ICC Brazil, 2023).

Similarly, Bieluczyk et al. (2024) emphasize the importance of integrating diverse practices such as no-tillage farming, well-managed pastures, and crop-livestock-forest integration to optimize mitigation benefits and promote more sustainable agricultural systems. Our study adds a policy dimension, demonstrating how the combination of sustainable agricultural practices with incentive-based policies and regulations, such as PNL35 and the ABC+ Program, can accelerate decarbonization and help achieve Brazil's climate goals. Furthermore, our research underscores the importance of integrating transportation and logistics into sustainability analyses of the soybean supply chain, showing that selecting more efficient and less polluting transportation modes significantly reduces GHG emissions and total supply chain costs.

Beyond its practical policy implications, this study contributes to the theoretical advancement of integrated assessment modeling by explicitly coupling agricultural land-use policies with freight transportation dynamics within a unified System Dynamics framework. Unlike sector-specific models, the proposed SD–IAM captures feedbacks, delays, and non-linear interactions between modal allocation, logistics costs, soil carbon dynamics, and emissions. By demonstrating how joint policy packages dominate isolated interventions in long-term cost–emission performance, the model provides a structural explanation of decarbonization pathways, extending the analytical scope of IAMs from macroeconomic climate assessment to export-oriented agri-logistics systems.

From a hypothesis-testing perspective, the policy implications derived here are fully consistent with H1–H4: modal diversification is a necessary condition for transport decarbonization (H1); sustainable agricultural practices provide scalable mitigation without undermining output (H2); their joint implementation generates synergistic emission reductions (H3); and integrated strategies dominate isolated interventions in long-term cost–emission performance (H4).

Finally, the results emphasize the need for an integrated approach combining transportation policies with sustainable agriculture. Modernizing logistical infrastructure and promoting low-carbon agricultural practices, when combined with the development of carbon markets, can position Brazil as a global leader in climate change mitigation. Effective mechanisms for monitoring and measuring emissions are essential to ensure transparency and compliance with climate targets (BCG, 2023; World Bank, 2023).

This coordinated approach not only reinforces Brazil's commitment to the Paris Agreement but also ensures sustainable and resilient economic growth, strengthening the country's role as a leader in combating climate change.

5 CONCLUSIONS

Global efforts to mitigate global warming focus on reducing emissions, seeking strategies that reconcile economic development with environmental preservation. In the Brazilian context, policies such as the Paris Agreement emphasize the importance of collective global action, as national initiatives alone have a limited impact on combating climate change.

However, Brazil has made progress in implementing sustainable practices across its production chains, particularly in agriculture, through government incentives and environmental policies. Despite these advances, these actions have not yet achieved a cost-effective balance in the short term, as climate damages continue to cause significant financial losses even with the adoption of low-carbon measures.

The soybean production sector, crucial to Brazil's economy, has been a key focus of environmental policies, particularly with practices like No-Tillage Systems (NTS). In addition to supporting established sustainable practices, expanding their scope to include new technologies and carbon reduction methods can further enhance the sector's sustainability. This research developed an Integrated Assessment Model (IAM) tailored to the soybean production chain, enabling scenario simulations and assessments of economic and environmental impacts.

Building on the limitations identified, future research can be guided by explicit and testable research questions. For instance: (i) how do extreme climate events such as El Niño and La Niña alter freight demand, infrastructure reliability, and emission trajectories across export corridors?; (ii) under which price and policy conditions does the substitution of diesel by biodiesel or ethanol in freight transport become cost-effective and emissions-efficient at scale?; and (iii) how do heterogeneous producer characteristics, such as farm size, access to credit, and risk aversion, affect the diffusion speed and spatial distribution of low-carbon agricultural and logistics practices?

Methodologically, these questions point to promising avenues for advancing the modeling framework. Future studies could integrate the current SD–IAM structure with agent-based or spatially explicit models to capture micro-level behavioral responses, regional heterogeneity, and corridor-specific dynamics. Such hybrid approaches would preserve the strengths of SD in representing system-wide feedbacks while enabling a more detailed examination of adoption behavior, coordination failures, and localized policy effects.

Promoting certification mechanisms and carbon credit trading, especially for practices like degraded pasture recovery and no-tillage farming, can generate substantial economic and environmental benefits. The interaction between the carbon credit market and programs like RenovaBio, through the CBIOs (Decarbonization Credits) market, offers another promising pathway to enhance decarbonization in energy-intensive sectors.

Despite the strengths of the System Dynamics–Integrated Assessment framework, this study has methodological limitations. First, the model represents producers, logistics operators, and markets in an aggregated manner, which limits the explicit representation of heterogeneous decision-making, behavioral adaptation, and spatial differentiation. Second, the diffusion of sustainable practices is modeled based on historical trends, which may not fully capture institutional barriers, risk perception, or strategic behavior by individual agents. Future research could address these limitations by coupling the present SD framework with agent-based or spatially explicit models, enabling the incorporation of behavioral heterogeneity, regional infrastructure disparities, and endogenous policy feedbacks. Such extensions would enhance micro-level realism while preserving the macro-level integrative capacity of the IAM approach.

This research demonstrates that combining sustainable agricultural practices, fiscal incentives, and analytical tools like integrated assessment models positions Brazil as a strategic player in climate change mitigation. However, challenges related to infrastructure and reliance on external funding demand ongoing efforts to overcome financial and regulatory barriers.

For Brazil to fully realize its potential, it will be essential to adopt integrated policies that reconcile environmental sustainability, economic competitiveness, and social inclusion, aligning regional specificities with global demands. Through international collaboration, technology transfer, and a robust regulatory framework, the country can consolidate its role as a leader in the transition to a low-carbon economy, promoting a more sustainable future.

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