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The Evolving Landscape of Global Soybean Trade: A Review of Market Dynamics and Sustainability Challenges

Henrique Friedrich de Oliveira[1], Peter Lengyel[2]

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A B S T R A C T

Between 2015 and 2025, the global soybean trade has experienced a major structural shift, marked by the growing export dominance of South America, particularly Brazil, alongside the rise of new geopolitical and environmental risks. This literature review draws on findings from 550 unique scholarly publications to analyze market trends, sustainability pressures, and technological advancements that are reshaping modern supply chains. The review highlights the far-reaching effects of the US-China trade war, most notably a roughly 70% drop in US soybean exports to China and a significant redistribution of market share toward Brazilian producers. By 2023, Brazil's soybean exports had climbed to around 102 million tonnes (approximately 3,744 million bushels), underscoring both the country's competitive strengths and the ripple effects of trade policy disruptions. From an environmental standpoint, soybean cultivation across South America more than doubled in area between 2000 and 2019, expanding to 55.1 million hectares and placing considerable strain on the Amazon and Cerrado biomes. Although the Soy Moratorium helped reduce direct deforestation in the Amazon by 57%, the Cerrado continues to lack adequate protection, and projections under a business-as-usual scenario point to ongoing forest loss and significant carbon emissions. On the technological front, innovations such as blockchain-enabled traceability, precision agriculture, and machine learning present promising opportunities to improve supply chain transparency and resilience. Blockchain pilot programs indicate that verified sustainability credentials could command a valuation premium of up to 15%. The review also identifies several key gaps in the existing research, including the long-term effects of climate extremes experienced in 2024–2025 on trade routes, insufficient post-2015 land-use data for Argentina, and the obstacles smallholder farmers face in adopting new technologies. Collectively, these findings underscore the pressing need for coordinated, multi-stakeholder action to safeguard the long-term sustainability and resilience of global soybean supply chains.

1. Introduction

Soybeans serve as a critical nexus in global food security; their superior amino acid profile makes them the indispensable protein base for livestock nutrition, while concurrently anchoring the international vegetable oil sector. The period from 2015 to 2025 witnessed a fundamental restructuring of global soybean trade, characterized by the consolidation of export dominance in South America, particularly Brazil, and the emergence of new vulnerabilities arising from geopolitical tensions, environmental pressures, and climate variability. This literature review synthesizes findings from 550 unique scholarly papers to examine the market dynamics, sustainability challenges, and technological innovations that have shaped contemporary soybean supply chains.

[1] Henrique Friedrich de Oliveira
Department of Agricultural and Business Digitalization, Faculty of Economics and Business, University of Debrecen
henrique.friedrich@econ.unideb.hu
[2] Peter Lengyel
Department of Agricultural and Business Digitalization, Faculty of Economics and Business, University of Debrecen
lengyel.peter@econ.unideb.hu

The change in export leadership reflects both fundamentals and policy shocks. Brazil's production expansion and logistics investments strengthened its competitiveness, but trade disputes and shifting policy signals also accelerated the reordering of trade routes. By 2023, Brazil had overtaken the United States as the leading exporter, and the two countries together accounted for more than 80% of global soybean exports (Friedrich de Oliveira & Lengyel, 2024). Trade network analyses covering 2003–2023 reinforce how concentrated this system has become: the United States and Brazil occupy the central exporter roles, while China dominates on the import side, creating a highly concentrated, bilateral trade structure (Friedrich de Oliveira & Lengyel, 2024). In practical terms, that concentration translates into systemic risk. When supply is this centralized, climate-driven yield shocks, infrastructure bottlenecks, or sudden policy changes in just one or two locations can transmit quickly across global feed and food markets.

The food security stakes of this level of trade concentration are high. China takes in most of the world's soybean imports, and depending largely on seaborne deliveries from just two main suppliers, leaves it particularly exposed when supply is disrupted (Qiao et al., 2023). Climate models also suggest that risk is not evenly spread: the ten largest producing countries, together responsible for about 97% of global output, could see average yield shifts from about -0.82% under a low-emissions pathway (RCP2.6) to roughly -5.22% under a high-emissions pathway (RCP8.5), even when CO_2 fertilization effects are accounted for (Qiao et al., 2023). In a tightly connected trading system, even modest production shocks can ripple outward, tightening availability and pushing up price volatility in import-dependent markets. At the same time, Brazil's rapid, export-driven expansion has been linked to deforestation, land concentration, and inequality, and added pressure on domestic food systems, raising legitimate questions about the long-run sustainability of current production trends (Peng et al., 2025).

This review is structured as follows: Section 2 outlines the systematic methodology employed to synthesize the 550 scholarly sources examined in this study. Section 3 provides a comprehensive literature review organized into three thematic pillars: geopolitical trade impacts, frontier expansion, and technological innovations. Section 4 presents the results of this thematic mapping, including the quantitative reorientation of trade flows. Section 5 discusses the identified research gaps and the 'intensification paradox,' while Section 6 provides concluding remarks. To guide this synthesis, the following research questions are addressed:

- RQ1: How has the 2018 US-China trade shock permanently restructured global soybean supply networks?
- RQ2: To what extent have governance mechanisms, such as the Soy Moratorium, succeeded in decoupling production from deforestation?
- RQ3: What are the primary socio-economic barriers preventing the scalable adoption of blockchain and AI-driven traceability?
- RQ4: What is the quantifiable impact of 2024–2025 climate extremes on the resilience of South American logistics corridors?

2. Methodology

To ensure a rigorous and transparent analysis of the fundamental transformations in the global soybean sector between 2015 and 2025, this study employs a systematic literature review (SLR) and thematic synthesis approach. The methodology was designed to capture the multi-dimensional nature of the trade, encompassing geopolitical, environmental, and technological variables.

2.1. Search Strategy and Information Sources

The systematic search was conducted using the SciSpace AI-powered research platform, utilizing natural language prompts built around the following core keywords and Boolean structures: 'soybean trade' AND 'geopolitics', 'soybean' AND 'deforestation', 'soybean' AND ('supply chain innovation' OR 'blockchain'), and 'soybean' AND 'trade diversion' AND 'Brazil'. This approach enabled an AI-enhanced retrieval process while maintaining the rigorous thematic focus required for a systematic synthesis.

2.2. Inclusion and Exclusion Criteria

To maintain high analytical standards, the following criteria were applied during the selection process:

- Temporal scope: Literature published between 2015 and 2025 was prioritized to capture the structural shifts following the 2018 trade war and the 2024–2025 climate extremes.
- Language: Only peer-reviewed journal articles and technical reports published in English were included to support international comparability.
- Relevance: Studies were excluded if they focused exclusively on molecular biology or agronomic yield trials without linking findings to wider market dynamics or environmental impacts.

The selection process followed a systematic two-stage screening protocol. While the SciSpace platform was utilized to enhance the efficiency of the discovery phase, a rigorous human verification process was maintained. In the initial stage, titles and abstracts were reviewed against the inclusion criteria to identify potentially relevant studies. In the second stage, a comprehensive full-text review of the remaining documents was conducted to ensure methodological rigor and alignment with the research pillars. This ensured that the AI-assisted retrieval aligned perfectly with the study's focus on market dynamics and sustainability, rather than purely agronomic data.

2.3. Thematic Synthesis and Data Extraction

Following the initial screening, the literature was categorized into three primary research pillars: (1) geopolitical shocks and market reorientation, (2) frontier expansion and environmental governance, and (3) technological and logistical innovations. Data extraction focused on identifying quantitative trends, such as the 70% collapse in US-China trade volumes. and qualitative insights regarding policy effectiveness and research gaps. To ensure international comparability and consistency across sources, all trade volumes were standardized to metric tonnes using the industry-standard conversion for soybeans: 1 bushel (bu) equals 60 pounds (lbs), or approximately 27.22 kilograms (kg). This thematic mapping allows for a holistic evaluation of the sector's resilience and long-term sustainability trajectories.

3. Literature Review

3.1. Geopolitical Impacts

Magnitude of Trade Destruction

Empirical studies document a dramatic collapse in US soybean exports to China following the implementation of tariffs. Richards et al. (2020) report that US exports to China "ground to a near halt", declining by approximately 20 million tonnes, a reduction of roughly 70% compared to the prior 12-month period. This trade destruction was not merely a temporary disruption; subsequent analyses using monthly data through mid-2025 confirm that import volumes from the United States declined sharply and did not fully revert to pre-tariff levels, indicating a structural shift in sourcing patterns (Song et al., 2025). Ex-ante modeling studies accurately predicted the magnitude of this disruption. Taheripour and Tyner (2018) estimated that a 25% Chinese tariff would reduce US soybean exports to China by approximately 69%, with corresponding multi-year welfare losses and trade reallocation effects. The strong alignment between model projections and observed outcomes highlights how sensitive bilateral agricultural trade is to tariff barriers, and how little room there is, in the short run, for demand-side substitution.

Trade Diversion to Brazil

The ability of Brazil to absorb diverted Chinese demand was facilitated by improvements in transport and port capacity, as well as seasonality advantages that allowed Brazilian soybeans to reach Chinese markets during periods when US supplies were less competitive. Spatial-competition models emphasize that competitiveness varies seasonally and with transport costs, and that infrastructure investments in Brazilian logistics amplified the country's capacity to fill diverted demand (Wilson et al., 2024).

Recent work by Hong and Lee (2025) introduces a geopolitical dimension to the analysis, finding evidence that geopolitical alignment and trade diversion reinforced Brazil's export expansion to China following the tariff shock. This suggests that trade reallocation was not solely a function of price and logistics but also reflected strategic considerations in sourcing decisions.

Asymmetric Price Transmission and Market Microstructure

The tariff episode created a wedge in the global soybean market, with asymmetric price effects across origins. Song et al. (2025) find that US soybean prices rose by approximately 43% following the tariff imposition, while non-US prices remained relatively stable, indicating incomplete pass-through of tariff costs and a structural reconfiguration of price relationships. Adjemian et al. (2021) document that the tariff actions lowered the US export basis at Gulf ports and depressed domestic prices relative to competitors, thereby incentivizing buyers to source from Brazil.

Beyond physical trade flows, the tariff shock altered market microstructure and price discovery mechanisms. Bandyopadhyay and Rajib (2023) document a deterioration in the informational leadership of US soybean futures and a weakening of price discovery following the trade conflict, suggesting longer-run changes in market leadership that extend beyond physical commodity flows. This finding has implications for hedging strategies and the global coordination of soybean markets.

3.2. Expansion of the South American Frontier

The expansion of soybean cultivation in South America has been a primary driver of land use change in the Amazon and Cerrado biomes, raising critical sustainability concerns. This section synthesizes evidence on the magnitude of area expansion, the direct and indirect drivers of deforestation, and the effectiveness of governance interventions designed to decouple soybean production from forest loss.

Magnitude and Geography of Soybean Expansion

Remote sensing studies document a dramatic increase in soybean cultivation area across South America during the 2000-2019 period. Song et al. (2021) report that cultivated soybean area more than doubled from 26.4 million hectares (Mha) to 55.1 Mha between 2000 and 2019, with most expansion occurring on previously converted pastures rather than directly on forests. However, the geographic distribution of this expansion reveals significant hotspots of environmental concern. Amazon soybean area increased from 0.4 Mha to 4.6 Mha over the same period, and nearly half of the active soy expansion frontiers were located in the Brazilian Cerrado (Song et al., 2021).

While soybean cultivation was not the sole direct driver of forest loss, it contributed substantially. Song et al. (2021) estimate that approximately 9% of forest loss across South America had been converted to soybean by 2016. This figure understates the full environmental impact, as indirect effects, including the displacement of cattle ranching into forested areas and infrastructure development that facilitates subsequent deforestation, are not captured in direct conversion metrics.

Projected Future Risks and Intensification Scenarios

Forward-looking modeling studies project continued deforestation risk under business-as-usual scenarios. Marin et al. (2022) estimate that continuation of current yield and area trends could convert an additional 5.7 Mha of forests and savannahs over a 15-year horizon, releasing approximately 1,955 million tonnes of CO_2 equivalent. In contrast, targeted intensification strategies that reallocate expansion to former livestock areas could yield 162 million tonnes of soy with no additional deforestation and approximately 58% lower warming impact than the baseline trend (Marin et al., 2022).

Infrastructure development amplifies deforestation risk by increasing the accessibility and economic viability of frontier areas. Frey et al. (2018) identified 2.3 Mha of planted soy in the Legal Amazon as of 2014 and an additional 14.7 Mha with high probability of conversion under existing infrastructure. Simulated infrastructure expansion scenarios increased high-risk areas by up to 2.1 Mha and could potentially release 4.8 petagrams of CO_2 if conversion occurred (Frey et al., 2018). These projections

underscore the importance of infrastructure planning and land-use zoning in determining future deforestation trajectories.

Effectiveness of the Soy Moratorium and Supply-Chain Governance

The Soy Moratorium, implemented in 2006 as a voluntary agreement among major soy traders to exclude soybeans grown on recently deforested land in the Amazon, represents a landmark supply-chain governance intervention. Empirical assessments document substantial reductions in direct forest-to-soy conversion following its implementation. Gollnow et al. (2022) report that Soy Moratorium signatories achieved a 57% reduction in direct deforestation for soy in the Amazon between 2006 and 2015. Kastens et al. (2017) find that the pre-Moratorium deforestation rate in Mato Grosso was over five times the post-Moratorium rate, and that the forest-to-soy conversion rate was more than twice as high before the intervention.

Despite these successes, the Soy Moratorium's geographic and institutional scope is limited. Gollnow et al. (2022) note that incomplete adoption of zero-deforestation commitments (ZDCs) leaves more than half of soy-suitable forests outside their reach. The Cerrado biome, which accounts for nearly half of active soy expansion frontiers, has not been subject to comparable supply-chain governance. Gollnow et al. (2022) estimate that ZDC implementation in the Cerrado with Amazon-like effectiveness could have reduced soy-driven deforestation by approximately 46%. This finding highlights the potential to extend supply-chain governance mechanisms beyond Amazon, though institutional and political barriers to such expansion remain significant.

Intensification Paradox and Frontier Dynamics

The relationship between agricultural intensification and deforestation is complex and context-dependent. Econometric and remote-sensing analyses indicate that crop and pasture intensification initially reduced local deforestation rates, but that crop intensification was associated with increased deforestation over longer time frames, suggesting rebound or leakage effects (Gollnow et al., 2022; Peng et al., 2025). This 'intensification paradox' arises when productivity gains lower per-unit production costs, increase profitability, and thereby incentivize area expansion unless countervailing policies or market mechanisms constrain land conversion (Gollnow et al., 2022). Studies in regions such as Matopiba, a frontier area spanning parts of Maranhão, Tocantins, Piauí, and Bahia, reveal that economic incentives and legal permissiveness lead many producers to clear native vegetation for soy when profitable (Gollnow et al., 2022; Peng et al., 2025). This finding underscores the critical role of regulation and enforcement in curbing further Cerrado loss, particularly in regions where land tenure is insecure and monitoring capacity is limited (Gollnow et al., 2022).

Argentina Evidence Gap

While the literature provides extensive quantitative data on soybean expansion and deforestation in Brazil, particularly in the Amazon and Cerrado biomes, comparable post-2015 land-use change and deforestation metrics for Argentina are notably absent from the corpus. Song et al. (2021) report continent-level patterns but do not disaggregate Brazil versus Argentina in their post-2015 quantified deforestation statistics. This gap constrains cross-country comparisons and limits the ability to assess whether governance interventions or production practices differ systematically between the two largest South American soybean producers.

3.3. Technological and Logistical Innovations

The period from 2015 to 2025 witnessed the emergence and piloting of a range of technological innovations designed to enhance the efficiency, traceability, and resilience of soybean supply chains. This section reviews evidence on precision agriculture, blockchain-based traceability systems, machine learning applications in logistics, and port-centric resilience strategies.

Precision Agriculture and Digital Transformation

Precision agriculture technologies—including GPS-guided machinery, variable-rate input application, remote sensing, and data analytics—have been widely promoted as tools to improve resource efficiency and farm profitability in soybean production. Reviews and case analyses report that digital and precision technologies can enhance pest and water management, optimize fertilizer application, and increase yields. However, most studies are qualitative or regionally focused rather than reporting standardized yield gains (Stroparo, 2024). Stroparo (2024) summarizes the financial and productive impacts of precision adoption in soy production, highlighting increased efficiency and profitability as reported outcomes.

Despite these documented benefits, adoption rates remain heterogeneous, with significant barriers for small and medium-scale producers. Capital requirements, technical expertise, and access to digital infrastructure constrain uptake, particularly in frontier regions where extension services and connectivity are limited. Foundational research in agricultural informatics emphasizes that the successful integration of ICT tools heavily relies on targeted sectoral competence frameworks and structured digital training to bridge the skills divide (Herdon et al., 2011). Furthermore, recent assessments of data-driven sustainability models demonstrate that small and medium-sized agricultural enterprises require adapted business frameworks and customized data-utilization capabilities to fully exploit their ecological and economic sustainability potential (Bálint et al., 2025). The literature lacks comprehensive adoption rate data across producer size classes, creating a significant gap in understanding the distributional impacts of digital transformation in soybean agriculture.

Blockchain-Based Traceability Systems

Blockchain technology has been proposed to enhance traceability, transparency, and trust in soybean supply chains, particularly for attributes such as non-GMO status, deforestation-free sourcing, and organic certification. Multiple studies describe prototype implementations and assess their technical feasibility and potential market impacts.

Salah et al. (2019) describe an Ethereum-based smart-contract architecture for soybean tracking that eliminates the need for central intermediaries to maintain transaction records, enabling decentralized verification of product provenance. Lucena et al. (2018) implemented a blockchain business network for grain quality tracking. They reported preliminary results suggesting a potential 15% increase in valuation for GM-free soy under a blockchain certification scenario. This valuation premium reflects consumer and buyer willingness to pay for verified sustainability attributes. However, the estimate is based on a limited pilot and may not generalize to large-scale commercial deployments.

Literature reviews document growing interest in blockchain as the dominant traceability information model in recent agricultural supply chain research (Malusare & Das, 2024; Anwar et al., 2022). However, practical implementations remain limited, and critical questions regarding scalability, interoperability, governance, and the distribution of costs and benefits across supply chain actors are not yet resolved. The literature does not provide empirical evidence on adoption rates among small- and medium-sized soybean producers or on the socio-economic impacts of blockchain deployment across diverse production contexts.

The challenges of shifting from traditional information architectures to decentralized tracing frameworks are not unique to global bulk commodities like soybeans. Earlier empirical work on localized agri-food sectors highlights that the foundational barrier to any advanced tracking innovation is the baseline interoperability of existing enterprise resource planning (ERP) and quality management systems (Füzesi et al., 2010). In the context of the Hungarian meat industry, the fragmentation of data environments across independent processing nodes demonstrated that technological deployment fails without standardized semantic data models, a structural bottleneck that directly mirrors the contemporary interoperability friction between multi-national soy grain networks (Füzesi et al., 2010). Furthermore, the ultimate scalability of these systems is heavily contingent upon end-user and consumer market validation. While blockchain pilots assume a structural premium for verified sustainability credentials, empirical assessments of consumer behavior indicate that acceptance is highly sensitive to perceived transparency, data privacy, and the socio-economic characteristics of the target market. Understanding this consumer-side dynamic is essential for soy supply chains, as the capital-intensive

deployment of blockchain-backed zero-deforestation or non-GMO certifications cannot achieve financial sustainability without robust, empirically verified market acceptance (Füzesi et al., 2020).

Machine Learning Applications in Logistics

Machine learning techniques have been applied to optimize logistics operations in soybean supply chains, focusing on predicting bottlenecks, reducing lead times, and improving resource allocation. A case study in Brazilian cooperatives combined discrete event simulation and machine learning to predict lead and queue times in soybean seed classification, enabling scenario testing to optimize workforce and machinery deployment and reduce logistics bottlenecks (Stroparo, 2024). This application illustrates the potential for data-driven decision support to enhance operational efficiency in post-harvest handling and processing.

Beyond farm-level and cooperative-level applications, machine learning has been proposed for broader supply chain optimization, including demand forecasting, route planning, and inventory management. However, the literature does not provide comprehensive assessments of the accuracy, cost-effectiveness, or adoption rates of these systems in commercial soybean supply chains.

Port and Transport Resilience

Logistics infrastructure plays a critical role in determining export competitiveness and supply chain resilience. Reviews of logistics in Brazil identify significant pre-harvest, harvest, transport, and storage losses that materially affect competitiveness and costs (Barbosa et al., 2020). Barbosa et al. (2020) emphasize the need for quantitative studies on transport and storage losses to determine their impact on rural profitability and export competitiveness.

Port-centric redesigns have been modeled as resilience and optimization levers in agri-commodity flows. Recent supply-chain simulations explore port-centric strategies for soybean flow redesign, assessing the potential for infrastructure investments and operational changes to reduce congestion and improve throughput (Hong & Lee, 2025; Peng et al., 2025). These modeling exercises provide valuable insights for infrastructure planning, though empirical validation of their projections remains limited.

Improvements in Brazilian transport and port capacity, combined with seasonality advantages, have amplified Brazil's competitiveness relative to US origins in several months of the year, contributing to Brazil's rising share of China-directed exports (Wilson et al., 2024). However, the literature does not provide comprehensive assessments of how recent climate events, particularly the 2024-2025 climate extremes, have affected port throughput, transport bottlenecks, or modal shifts in soybean logistics.

4. Results

4.1. Geopolitical Impacts: US-China Trade Tensions and Trade Diversion

The 2018 imposition of retaliatory tariffs by China on US soybeans represents one of the most significant trade policy shocks in recent agricultural history, producing measurable and persistent changes in global soybean trade flows. The tariff episode resulted in substantial trade destruction, asymmetric price effects, and a structural reallocation of market shares toward South American suppliers.

The following table provides a thematic synthesis of the core research pillars examined in this review, highlighting key findings and representative scholarly sources across global soybean trade dynamics.

Table 1. Thematic Synthesis of Global Soybean Trade Literature (2015–2025)

Research Pillar	***Key Dynamics & Findings***	***Representative Sources***
Geopolitical Shocks	~70% collapse in US-China bilateral trade; structural diversion to Brazil (+10M tonnes); 43% increase in US export basis costs.	Richards et al. (2020); Song et al. (2025); Taheripour & Tyner (2018)

Research Pillar	*Key Dynamics & Findings*	*Representative Sources*
Frontier Expansion	Cultivated area doubled from \$26.4\$ to \$55.1 \text{ Mha}\$; Amazon soy area grew from \$0.4\$ to \$4.6 \text{ Mha}\$; 9% of forest loss converted to soy by 2016.	Song et al. (2021); Frey et al. (2018)
Governance & Sustainability	Soy Moratorium achieved 57% reduction in direct Amazon deforestation; "Intensification Paradox" suggests long-term rebound effects in land clearing.	Gollnow et al. (2022); Kastens et al. (2017)
Supply Chain Innovation	15% valuation premium for blockchain-verified GM-free soy; ML applications in post-harvest logistics; adoption barriers for smallholders.	Lucena et al. (2018); Stroparo (2024); Salah et al. (2019)

4.2. Trade Diversion to Brazil

The decline in US shipments was accompanied by a rapid increase in Brazilian exports to China. Richards et al. (2020) document that Brazil increased shipments to China by approximately 10 million tonnes in late 2018 and early 2019, partially offsetting the US decline. Taheripour and Tyner (2018) projected a 27% increase in Brazil's exports to China under the tariff scenario, a forecast consistent with observed flows. Dhoubhadel et al. (2023) provide ex-post econometric evidence confirming significant trade diversion from US origins toward Brazil during the tariff episode.

The structural reallocation of these global flows is visually synthesized in Figure 1, highlighting the shift from US bilateral corridors to Brazilian dominance in the Chinese market.

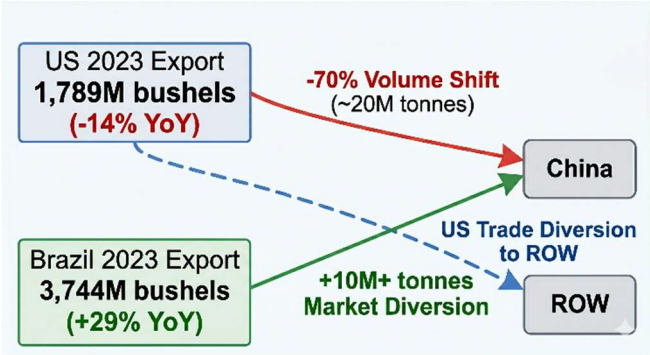


Figure 1. Strategic Reorientation of Global Soybean Trade Flows (2018–2025)
Red arrows indicate the 70% volume reduction in the US-China corridor. Green arrows represent Brazil's market capture (over 10M tonnes in immediate diversion). The dashed blue line signifies the rerouting of US supplies to the Rest of the World (ROW). Sources: [aggregated 20-year export analysis, 2023]; Richards et al. (2020). Abbreviations: YoY = Year-on-Year (comparison of 2023 data against 2022); M = Million.

The structural reallocation of these global flows, as synthesized in Figure 1, demonstrates that the trade shock triggered more than a temporary fluctuation. The 70% collapse in bilateral US-China trade volumes created a supply vacuum that was strategically occupied by Brazilian producers, whose total exports reached a record 102 million tonnes (3,744 million bushels) in 2023, a 29% Year-on-Year (YoY) increase. Furthermore, Figure 1 highlights the 'Trade Diversion' effect: US exporters, facing restricted access to their primary market, were forced to diversify into secondary markets (ROW) to absorb surplus production. This systemic rerouting confirms that the 2018 tariff disruption catalyzed a permanent shift in global logistics and export competitiveness, positioning Brazil as the dominant supplier for the Chinese market while forcing a broader, lower-margin distribution strategy for US soy.

Aggregate export data illustrate the cumulative effect of this reallocation. A 20-year synthesis reports that Brazil's 2023 soybean exports reached approximately 102 million tonnes (3,744 million bushels), representing a 29% year-on-year increase, while US shipments declined to about 49 million tonnes (1,789 million bushels), a 14% year-on-year decrease [aggregated 20-year export analysis, 2023]. This

divergence reflects not only the immediate tariff shock but also underlying competitive advantages in Brazilian production and logistics that were amplified by the policy disruption.

5. Discussion

The synthesis of 550 unique papers reveals several critical gaps in the current literature that limit the ability to forecast future trade dynamics, assess sustainability outcomes, and design effective policy interventions. These research priorities are visually synthesized in Figure 2, which categorizes identified gaps according to their research urgency and the current availability of empirical data.

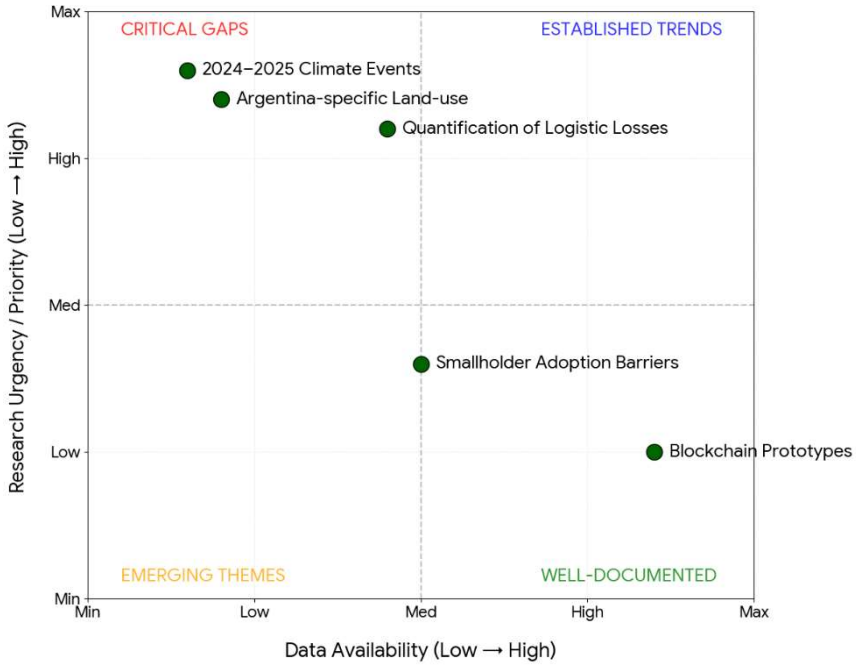


Figure 2. Research Gap Matrix: Global Soybean Trade (2015-2025)

As illustrated in Figure 2, the matrix identifies the long-term impacts of 2024-2025 climate events on trade routes as a critical research priority, for which empirical analyses are currently absent. Similarly, the lack of standardized post-2015 land-use and deforestation metrics for Argentina, compared to the extensive data available for the Brazilian Amazon and Cerrado, represents a significant barrier to comprehensive cross-country assessments. While technological innovations like blockchain have a growing body of pilot data, their scalable adoption and the quantification of logistic losses remain documented but secondary priorities compared to immediate climate and regional data needs. This section identifies five priority areas for future research based on this matrix:

5.1. Long-Term Impacts of 2024-2025 Climate Events on Trade Routes

The synthesis of the current corpus reveals a significant lack of empirical analysis regarding the long-term structural impacts of the 2024-2025 climate extremes on global soybean trade routes. While the immediate disruptions caused by these events are widely reported in trade media, scholarly literature has yet to quantify their multi-year consequences for transport bottlenecks or potential shifts in logistics modalities. Climate extremes documented during this period, specifically the severe droughts affecting river navigation in the Amazon basin and the intense flooding disrupting southern port operations, have demonstrated the potential to alter export volumes and routing resilience fundamentally. For instance, prolonged low water levels in key river systems forced a temporary reliance on more expensive road transport. However, the permanent implications for infrastructure investment and modal split remain unexamined.

Furthermore, concurrent heat stress, which is impacting yields across primary production zones, has introduced new layers of supply-side volatility that existing trade models have not fully integrated. The

absence of longitudinal studies quantifying these disruptions represents a critical gap in the literature. Without such data, it is impossible to accurately forecast market adaptation strategies or the necessary resilience-oriented infrastructure investments for the 2026–2030 horizon. Therefore, targeted empirical monitoring of the 2024–2026 period is urgently required, with a focus on port throughput stability, supply chain transparency, and the long-term economic viability of climate-vulnerable transport corridors.

5.2. Argentina-Specific Land-Use Data

A significant disparity exists in the spatial and temporal resolution of land-use data between the primary South American soybean producers. While the scholarly literature provides extensive quantitative data on expansion and deforestation in Brazil—particularly focusing on the Amazon and Cerrado biomes—comparable post-2015 land-use change and deforestation metrics for Argentina are notably absent from the current research corpus.

Current studies, such as Song et al. (2021), report continent-level patterns but do not disaggregate Brazil versus Argentina in their post-2015 quantified deforestation statistics. This empirical gap represents a significant constraint for the academic community, as it limits the ability to perform rigorous cross-country comparisons. Furthermore, it hinders assessments of whether governance interventions, production practices, or environmental outcomes differ systematically between the two largest South American soybean producers. To resolve these dynamics, standardized remote-sensing assessments of land-use change, particularly in Argentina's soybean-producing regions, are urgently needed to enable a more holistic understanding of land-use trajectories across South America.

5.3. Quantification of Logistic Losses

Logistics infrastructure, specifically port capacity and transport networks, plays a critical role in determining export competitiveness and supply chain resilience. However, significant pre-harvest, harvest, transport, and storage losses materially affect competitiveness and costs, particularly in major exporting regions. Barbosa et al. (2020) emphasize the urgent need for quantitative studies on these transport and storage losses to assess their specific economic impacts on rural profitability and export competitiveness. While current qualitative reviews identify substantial losses at multiple stages of the supply chain, the existing literature lacks standardized measurements of loss rates or their detailed economic consequences. Furthermore, the literature does not yet provide comprehensive assessments of how the 2024-2025 climate extremes have affected port throughput or logistics bottlenecks, representing an intersectional gap between climate and logistics research. Standardizing such data is essential for prioritizing strategic infrastructure investments, optimizing logistics operations, and accurately assessing the full environmental footprint of soybean production and trade.

5.4. Adoption Barriers and Smallholder Inclusion in Technological Innovations

While blockchain technology, precision agriculture, and machine learning systems have been successfully prototyped and piloted in controlled settings, empirical evidence regarding their actual adoption rates among small and medium-scale soybean producers remains scarce. Much of the current literature focuses on the technical feasibility of these systems, such as the Ethereum-based smart contracts described by Salah et al. (2019) and the blockchain-based quality assurance models proposed by Lucena et al. (2018). However, the socio-economic impacts and distributional consequences of these technologies are not yet well understood. Significant barriers to inclusive technological transformation persist, including high capital requirements, a lack of specialized technical expertise, and limited access to reliable digital infrastructure in frontier regions. For instance, recent evidence from Zimbabwe (2024) indicates minimal uptake of AI and digital tools in smallholder soybean production, highlighting the challenges of technology diffusion in resource-constrained environments. Furthermore, the literature lacks comprehensive data on how the costs and benefits of digital traceability and precision tools are distributed across diverse supply chain actors. To address this gap, future research should employ mixed-methods assessments to identify specific adoption barriers and the socio-economic drivers of smallholder inclusion. Understanding these dynamics is essential for designing policies and private-sector initiatives that ensure technological innovations contribute to equitable and sustainable agricultural development rather than exacerbating existing inequalities.

5.5. Longitudinal Studies of Agricultural Intensification and Deforestation

The relationship between agricultural intensification and deforestation remains complex and context-dependent, presenting what is often termed the "intensification paradox". Current econometric and remote-sensing analyses indicate that while crop and pasture intensification may initially reduce local

deforestation rates, such productivity gains are often associated with increased deforestation over longer time frames. This phenomenon occurs when higher yields incentivize further land expansion, unless robust policy mechanisms constrain it. While forward-looking modeling studies, such as those by Marin et al. (2022), suggest that targeted intensification in former livestock areas could significantly reduce warming impacts and prevent additional forest loss, empirical validation of these scenarios over long horizons is lacking. The existing literature presents mixed evidence regarding the causal pathways linking intensification to landscape-scale land-use change and the spatial dynamics of "leakage", where conservation in one area leads to increased clearing in another. To resolve these contradictions, there is a critical need for longitudinal panel data studies that link farm-level practices directly to regional deforestation outcomes. Such research is essential to identify the specific policy levers and market mechanisms needed to prevent rebound effects and ensure that sustainable intensification strategies deliver the intended environmental benefits.

6. Conclusion

The period from 2015 to 2025 witnessed a fundamental restructuring of global soybean trade, characterized by Brazil's consolidation of export dominance, the disruptive impacts of US-China trade tensions, the expansion of the South American agricultural frontier into environmentally sensitive biomes, and the emergence of technological innovations designed to enhance supply chain resilience and transparency. The literature synthesized in this review documents substantial trade destruction and diversion following the 2018 tariff episode, with US exports to China declining by approximately 70% and Brazil increasing shipments by approximately 10 million tonnes in the immediate aftermath (Richards et al., 2020). By 2023, Brazil's exports reached approximately 102 million tonnes, while US shipments declined to about 49 million tonnes, reflecting both the tariff shock and underlying competitive advantages in Brazilian production and logistics (Friedrich de Oliveira & Lengyel, 2024).

The environmental consequences of this trade expansion are substantial. Soybean cultivation area in South America more than doubled from 26.4 Mha to 55.1 Mha between 2000 and 2019, with significant expansion in the Amazon and Cerrado biomes (Song et al., 2021). Governance interventions, such as the Soy Moratorium, achieved a 57% reduction in direct soy deforestation in the Amazon, demonstrating the potential for supply-chain governance to decouple production from forest loss. However, incomplete adoption of zero-deforestation commitments leaves more than half of soy-suitable forests outside their reach, and the Cerrado biome remains largely unprotected (Gollnow et al., 2022).

Technological innovations, including precision agriculture, blockchain traceability systems, and machine learning applications, offer pathways to enhance efficiency, transparency, and sustainability. Blockchain pilots suggest a potential 15% added valuation for GM-free soy under verified certification scenarios (Lucena et al., 2018), while machine learning applications have demonstrated the potential to reduce logistics bottlenecks in post-harvest operations (Stroparo, 2024). However, adoption rates remain heterogeneous, and critical questions regarding scalability, interoperability, and the distribution of costs and benefits across supply chain actors remain unresolved.

The critical gap analysis identifies five priority areas for future research: (1) empirical monitoring of the long-term impacts of 2024-2025 climate events on trade routes and port throughput; (2) standardized remote-sensing assessments of land-use change in Argentina's soybean-producing regions; (3) quantitative studies on transport and storage losses to assess their economic impacts on competitiveness; (4) mixed-methods assessments of adoption barriers and the distributional impacts of technological innovations among small and medium producers; and (5) longitudinal studies linking farm-level intensification practices to regional deforestation outcomes to resolve the intensification paradox and inform sustainable intensification strategies.

Global soybean supply chains have become more resilient in terms of logistics and sourcing diversification, yet they face intensifying environmental scrutiny and climate-related vulnerabilities. The concentration of production and trade in a small number of countries elevates systemic risk, and the expansion of cultivation into environmentally sensitive biomes raises fundamental questions about the long-term sustainability of current production trajectories. Addressing these challenges will require coordinated action across supply chain actors, governments, and civil society to strengthen governance

mechanisms, promote sustainable intensification, and ensure that technological innovations are accessible to producers of all scales.

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