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Global soybean trade dynamics: Drivers, impacts, and sustainability

Dailiang Peng,[1,2,*] Hongchi Zhang,[1,2,3] Yizhou Zhang,[1,2,3] Le Yu,[4,5,*] Minpeng Chen,[6] Jing M. Chen,[7,8] Liangzhi You,[9,10] Peiwu Li,[11,12] Jianguo Liu,[13] Xiaoyang Zhang,[14] Damien Arvor,[15] Patrick Kuchler,[16] Jianxi Huang,[17] Hankui Zhang,[14] Pengyu Hao,[18] Jingfeng Huang,[19] Zhou Shi,[19] Fumin Wang,[19] Kaishan Song,[20] Zhiyuan Pei,[21] Cunjun Li,[22] Yue Xie,[23] Qi Zhang,[11] Meijuan Liang,[11] Hui Li,[11] Jinkang Hu,[1,2,3] Zihang Lou,[19] Shijun Zheng,[4] Xuxiang Feng,[24] Hao Peng,[25] Xiyu Li,[4] Alfredo Huete,[26] and Bing Zhang[1,2,3,*]

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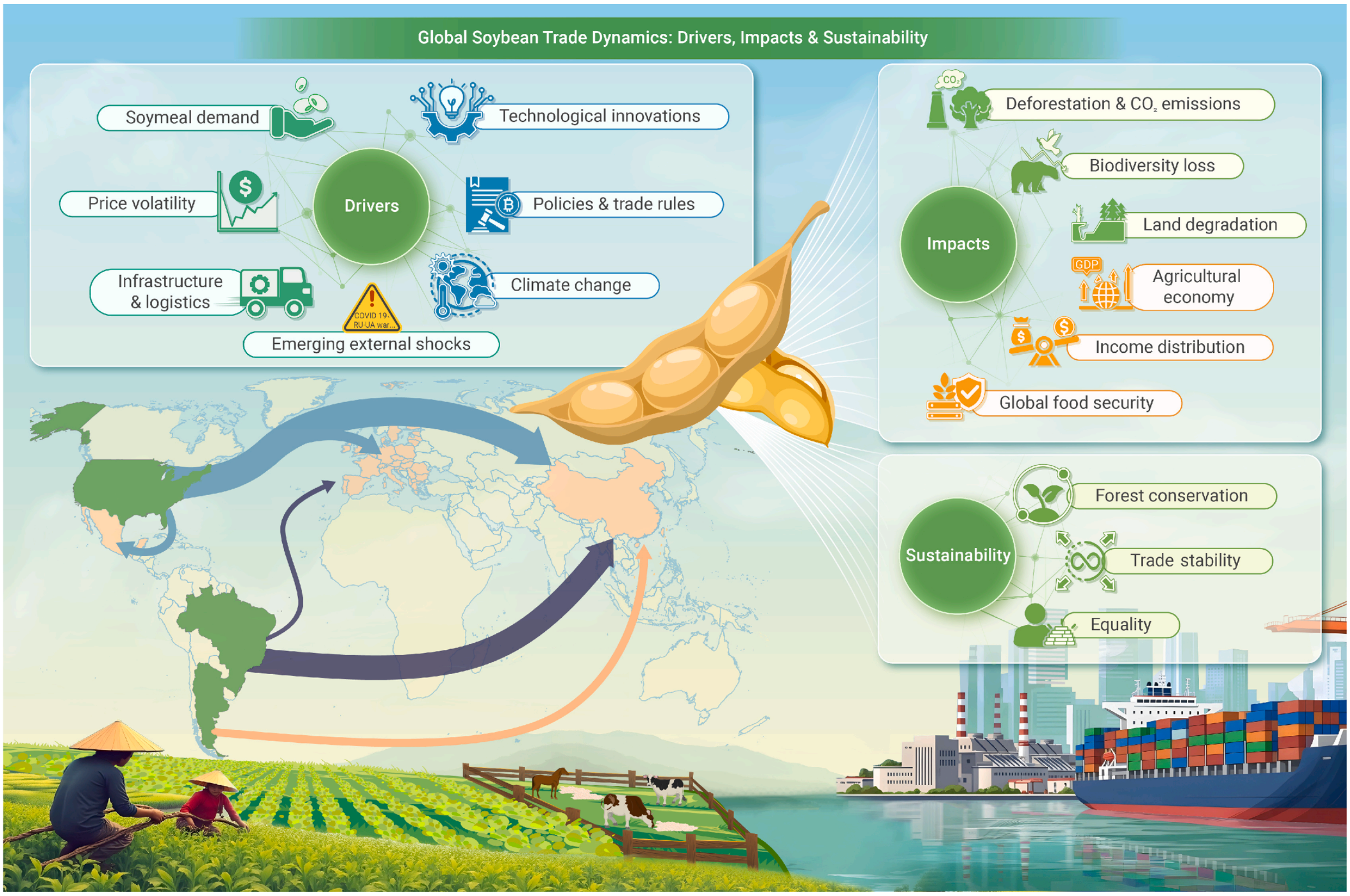
Received: June 11, 2025; Accepted: September 25, 2025; https://doi.org/10.1016/j.xinn.2025.101124

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Global soybean trade has rapidly expanded, reshaping agricultural patterns and global markets.
- Trade dynamics are driven by demand shifts, supply chains, policies, technologies, and climate risks.
- Expansion has caused deforestation, biodiversity loss, inequality, and food security challenges.
- Sustainable pathways require policy coordination, technological innovation, and global cooperation.

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Received: June 11, 2025; Accepted: September 25, 2025; https://doi.org/10.1016/j.xinn.2025.101124

Citation: Peng D., Zhang H., Zhang Y., et al., (2026). Global soybean trade dynamics: Drivers, impacts, and sustainability. The Innovation **7(2)**, 101124.

Since the 20th century, the global soybean trade has undergone major changes, shaped by rising demand, climate-related risks, and shifting international dynamics. Despite its global importance, important gaps remain in understanding the complex drivers and sustainability challenges of this transformation. This review synthesizes both direct and indirect forces reshaping trade flows, spanning market dynamics, supply chain logistics, policy shifts, and technological innovation. We examine how soybean trade expansion has impacted deforestation, inequality, and food security, and assess the responses of governments and companies to address these challenges. Finally, we provide a forward-looking perspective on the strategic pathways needed to ensure a more resilient and sustainable global soybean system. The integrated insights offered in this review can inform sustainable trade strategies and foster cross-scale policy coordination for a more resilient global agri-food system.

INTRODUCTION

Soybean (*Glycine max*) is a versatile crop central to modern agri-food systems, valued for its high protein and oil content, and underpins a wide array of sectors, including livestock feed, human nutrition and health, industrial processing, and renewable energy. Its strategic importance stems from its indispensable contribution to meat production and nutritional supply in emerging economies.[1,2] The global soybean harvested area increased from 23.82 Mha in 1960 to 136.90 Mha in 2024.[3] However, the expansion of soybean cultivation has raised significant sustainability concerns, particularly in South America, where it has become a major driver of deforestation and habitat conversion, posing threats to global warming and biodiversity.[1,4] The globalization of the soybean trade has also resulted in pronounced telecoupled environmental and socio-economic effects, whereby consumption in distant markets imposes external impacts on producing regions.[5–7] This global interdependence positions soybean at the intersection of agricultural development, environmental governance, and international trade policies, prompting increasing efforts to reconcile its economic value with its ecological footprint.[8–11]

The transformation of soybeans from a regionally domesticated crop in East Asia into a globally traded commodity has been shaped by a confluence of historical, agronomic, and economic transitions (Figure 1B). Originating in China over three millennia ago, soybean was domesticated and subsequently embedded as a dietary and agricultural staple in East Asian societies.[12] Its international dissemination began in the early twentieth century with its introduction to North America and beyond.[13] During the 1930s and 1940s, China served as a major exporter of soybean oil and protein to industrializing nations.[14] The mid-20th century served as a crucial juncture in the global restructuring of soybean production.[8] With the widespread adoption of high-yielding varieties and mechanized farming practices, the United States rapidly rose to global leadership in both soybean production and exports[15] and surpassed China by the 1950s[16] Since the 1970s, South American countries, primarily Brazil and Argentina, have dramatically increased their cultivated areas through the introduction of improved cultivars and extensive land conversion.[3] Consequently, Brazil surpassed the United States as the world's leading soybean exporter in 2012, reaching an export volume of 98.8 million tons by 2024, which accounts for approximately 50% of global soybean exports (Figures 1A and 1B).[4,17] The United States remained the second-largest exporter, while Argentina has maintained a relatively greater emphasis on processed soybean products, serving as a key supplier of soybean meal and oil in international markets. According to projections by the United States Department of Agriculture,[18] by the 2024/25 marketing year, Brazil, the United States, and Argentina will collectively account for approximately 80% of global soybean production, with Brazil contributing

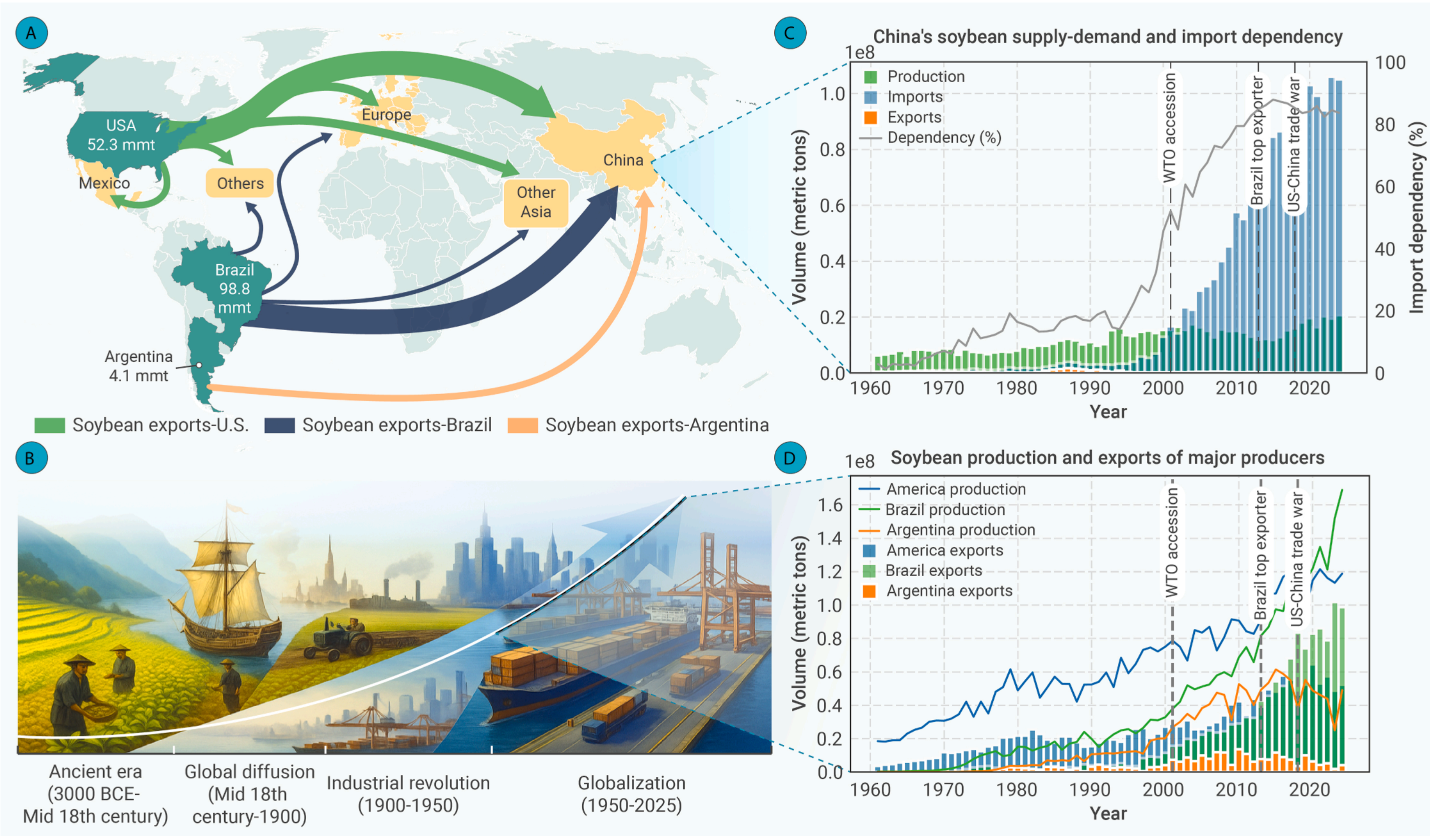

Figure 1. Global soybean trade dynamics (A) Global soybean export flows (2024). Arrow thickness indicates export volume; numbers shown for the United States, Brazil, and Argentina represent each country's soybean exports in 2024 (mmt, million metric tons). Data were sourced from The International Trade Centre (ITC). (B) The evolutionary stages of the global soybean trade. (C) Historical changes of soybean production and trade in China (1961–2024). Bars show production, import, and export volumes; the line illustrates China's dependence on soybean imports. Data were sourced from Food and Agriculture Organization (FAO).[3] (D) Historical changes in soybean production and exports in the United States, Brazil, and Argentina (1960–2024). Lines represent production, while bars indicate export volumes. Data were sourced from FAO.[3]

40%, the United States 28%, and Argentina 12%. The global soybean supply chain has become increasingly concentrated, with a limited number of vertically integrated multinational agribusinesses holding sway over crucial activities, spanning from production in South America to consumption in Asia.[19] This structural concentration has amplified the supply chain's vulnerability to geopolitical disruptions.

On the demand side, China has emerged as the dominant force shaping the global soybean trade. Since the late 1990s, surging domestic demand for meat and edible oils, combined with constraints on arable land, has markedly reduced China's soybean self-sufficiency. Following its accession to the World Trade Organization in 2001, China's soybean imports grew rapidly, reaching approximately 105 million tons in 2024, with an import dependency ratio of 85% (Figure 1C). This dramatic rise in demand has transformed global trade routes, resulting in an unprecedented concentration of soybean flows. Geopolitical tensions have further intensified the volatility of this system. The 2018–2019 United States-China trade war prompted China to shift imports toward Brazil and other suppliers.[5,20] A renewed round of trade frictions in 2024–2025 has further diminished the United States market share in China, reinforcing South America's export dominance and potentially accelerating the emergence of a more multipolar trade pattern. Beyond China, several other regions significantly contribute to global soybean demand, driven by diverse consumption patterns. The European Union (EU) remains a major importer of soybean meal for livestock feed, importing over 18 million tons annually.[3] Southeast Asia, including countries such as Vietnam, Indonesia, and Thailand, has also experienced rapid growth in soybean imports due to the expansion of animal feed industries. Although Argentina ranks as the world's third-largest soybean producer, its booming soybean oil and meal processing industries have also generated considerable import demand for raw soybeans. These regional variations highlight the need to recognize a more diversified and multi-polar global demand landscape in the soybean trade.

The soybean trade is not merely a mechanism for economic exchange. It also serves as a conduit for environmental and geopolitical externalities.[21] As climate variability, geopolitical tensions, and market uncertainties become increasingly entangled, the soybean trade has evolved into a contested domain between the goals of economic efficiency and ecological integrity.[22] The need to construct a soybean supply chain that is both efficient and environmentally sustainable has emerged as a critical challenge in global governance.[6,23] The concentration of trade among a limited number of producing and consuming countries has created intricate patterns of interdependence, simultaneously generating conflict risks and reinforcing systemic vulnerabilities in food security, industrial development, and environmental protection. These intertwined challenges expose overlooked linkages among trade dynamics, ecological impacts, and governance mechanisms, underscoring the urgency of a more integrated analytical approach. To elucidate the mechanisms underlying these evolving dynamics, this paper aims to (1) identify the direct and indirect drivers of soybean trade reconfiguration, including market demand shifts, price mechanisms, supply chain restructuring, policy interventions, and climate factors; (2) assess the socio-ecological feedback resulting from trade expansion, such as deforestation, water and soil stress, income distribution, and food security implications; and (3) explore governance responses such as including policy instruments, corporate initiatives, and technological innovations that may enable a transition toward more sustainable trade paradigms. This review makes a novel contribution by integrating the telecoupling framework, sustainability governance, and agri-food trade into a unified analytical perspective. Adopting a multi-scalar and cross-disciplinary approach, we link trade drivers, socio-ecological feedback, and governance mechanisms across interconnected regions. By embedding telecoupled interactions among producers, consumers, and intermediaries and examining how regulatory, corporate, and technological instruments shape trade systems, we identify previously overlooked patterns of feedback, tension, and opportunity. This perspective advances both sustainability science and global trade

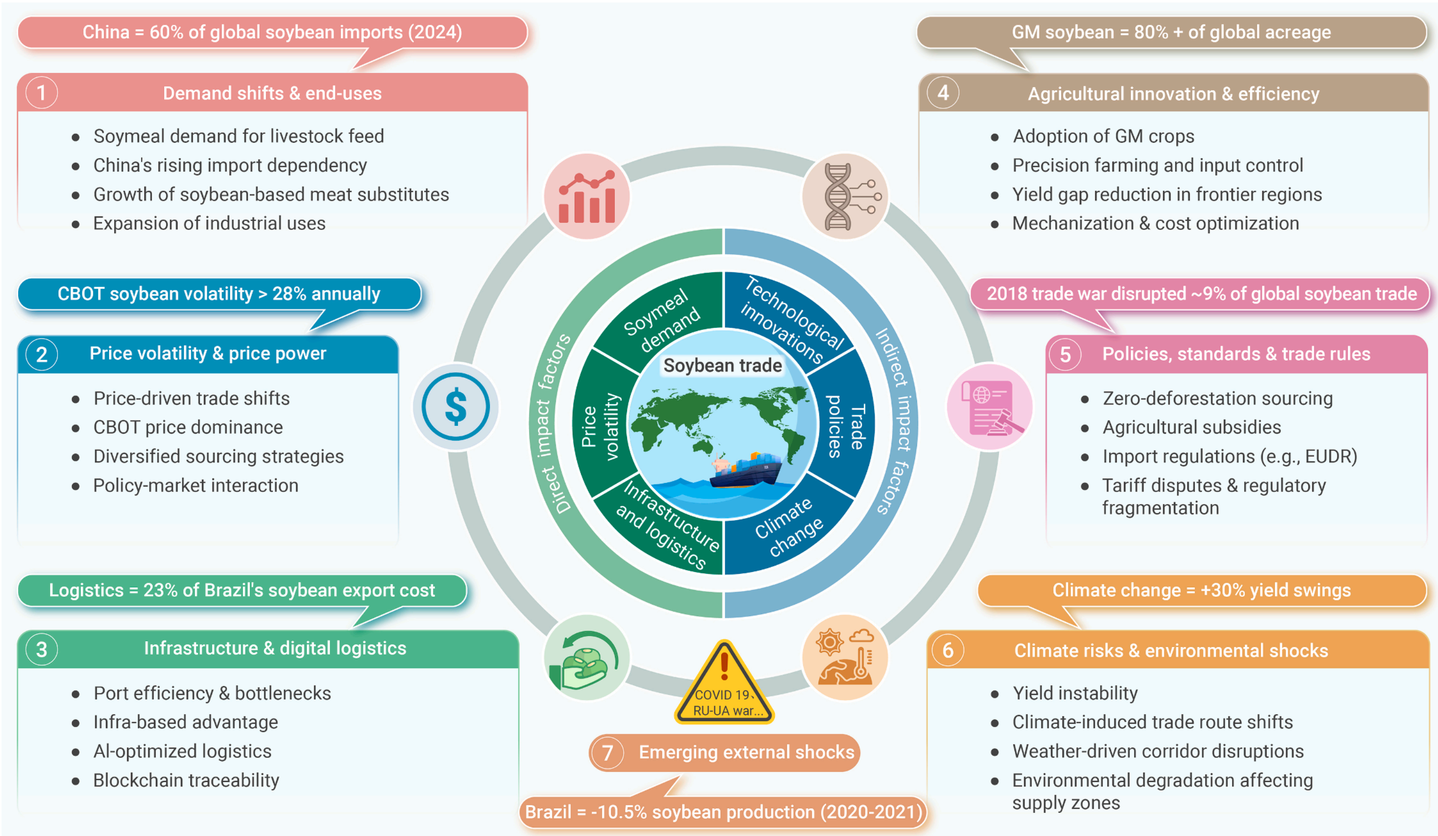

Figure 2. Drivers of global soybean trade dynamics RA, Russia; UA, Ukraine. Data were sourced from ITC,[17] MacroTrends,[53] Valdes et al.,[54] Briefs,[55] FAO,[3] United States Department of Agriculture (USDA),[56] Ray et al.,[57] Hamed et al.,[31] and Da Silva et al.[58]

governance while offering actionable insights for fostering a more resilient and equitable soybean system.

METHOD AND TERMINOLOGY

This review adopts a systematic and thematic approach to synthesize current knowledge of the global soybean trade, with particular attention to its drivers, socio-ecological impacts, and sustainability governance. Literature was retrieved from major academic databases (Web of Science, Scopus, and PubMed), with supplemental searches via Google Scholar to incorporate gray literature such as policy reports and industry publications. The search spanned publications from January 2000 to May 2025 to capture both foundational and recent developments. Search terms were structured around three thematic dimensions: drivers (e.g., demand shifts, climate change, and policy instruments), impacts (e.g., deforestation, food security, and inequality), and governance (e.g., zero-deforestation commitments, traceability, and corporate initiatives). We used Boolean operators to refine results. Studies were included if they (1) focused on international or regional soybean trade dynamics, (2) demonstrated methodological rigor (peer-reviewed or institutional quality), and (3) addressed relevant thematic content with both global syntheses and region-specific studies (particularly from Brazil, Argentina, the United States, China, Southeast Asia, and sub-Saharan Africa).

Throughout this review, “resilience” refers to the capacity of socio-ecological or economic systems such as agroecosystems, trade networks, or communities to absorb shocks (e.g., market volatility and climate extremes) and recover without losing core functions. Sustainability describes broader long-term viability and balance, encompassing environmental integrity, economic efficiency, and social equity across the soybean trade and governance. Where appropriate, domain-specific qualifiers (e.g., “agroecological resilience” and “trade sustainability”) are applied for clarity. Technological diffusion denotes the spread and adoption of innovations such as improved cultivars, digital monitoring, or sustainable farming practices across regions and actors. Traceability refers to the ability to track and verify the origin, movement, and production conditions of soybeans along the supply chain, often as part of sustainability commitments.

DRIVERS OF GLOBAL SOYBEAN TRADE DYNAMICS

Global soybean trade routes are experiencing profound shifts driven by a continually growing array of intricate and diverse factors.[24–27] Systematically unpacking the multidimensional drivers of global soybean trade is essential for understanding the evolution of contemporary agricultural globalization, building resilient food systems, and advancing sustainable development agendas.[28–30] The global soybean trade is driven by demand under the combined influence of population growth, changing consumption patterns, policy guidance, and ecological sustainability concerns. Shifts in market demand patterns, price volatility, restructuring of global logistics, technological advances in agriculture, policy competition, and climate change are redefining the global pattern of soybean production and trade.[20,30–33]

Understanding the dynamics of the global soybean trade requires distinguishing between different layers of causality. In this review, we classify drivers into two broad categories: direct and indirect, based on their temporal proximity, mechanistic immediacy, and causal relationship to trade flows. This framework draws conceptually from environmental governance and land use change literature, particularly the distinction between proximate and underlying drivers.[34–36] Direct drivers are defined as factors that exert an immediate and observable influence on trade volumes, prices, or flows. These include short-term shifts in demand, supply chain logistics, and price volatility. In contrast, indirect drivers refer to structural forces that shape the broader context in which trade occurs, such as policy instruments, technological innovations, climate pressures, or socioeconomic transitions.

Direct drivers of the soybean trade

Shifting demand in the international soybean market. Changes in international soybean demand are some of the primary drivers shaping the structure of the global soybean trade (Figure 2), particularly reflected in the expansion of the animal feed industry and rising per capita protein consumption.[37,38] Like many other global commodity trades, the soybean trade is fundamentally shaped by the geographic mismatch between regions with abundant arable land and those with a high population density.[39] According to FAO estimates, over 70% of global soybean production is ultimately processed into soybean meal for use in livestock feed, especially for high-yield meat-producing animals such as pigs, poultry, and cattle, due to the high protein content and favorable amino acid profile of soybean.[40] As the world's largest soybean importer, China has seen its import volume surge from around 12 million tons in 2000 to more than 105 million tons in 2024, accounting for over 60% of global imports.[17] This change has been largely driven by diet upgrades associated with improvements in living standards and changing consumption patterns.[41] China produces less than 20% of the soybeans it consumes and relies increasingly on imports due to limited arable land. In the late 1990s, the outbreak of bovine spongiform encephalopathy in Europe prompted a fundamental shift in animal feed formulation. The resulting ban on meat and bone meal led to a surge in demand for plant-based protein sources such as soybean meal, significantly increasing the European Union's soybean imports.[42] This rising reliance of the European Union on soybean meal, particularly for livestock feed, has become a major driver of soybean expansion in Brazil, Argentina, and other producing countries.[43]

Beyond its role in protein feed, the rising demand for soybean oil is an equally significant driver of the global soybean trade. In China, soybean oil is the most widely consumed vegetable oil, and its consumption has grown steadily alongside rising incomes and increasingly diversified diets.[44,45] This trend is further reinforced by China's substantial soybean crushing capacity, which enables the simultaneous production of soybean meal and oil from imported raw beans.[46] Similar consumption trends are evident in other developing countries, notably India, where soybean oil has become the second most important edible oil after palm oil, serving as an affordable and accessible source of dietary fat for large segments of the population.[47] In 2023, India's soybean oil imports reached approximately 3.5 million tons, making it the largest importer globally.

The growing human and industrial consumption of soybean has significantly driven up its global demand. In developed countries, plant-based diets are becoming mainstream and have accelerated the growth of soy-based meat alternatives driven by growing health awareness, environmental concerns, and ethical considerations.[48,49] Across developing countries in Africa and Asia, soybeans continue to serve as a staple source of protein. Meanwhile, industrial consumption of soybeans is expanding: in the United States, over 40% of soybean oil is used for biodiesel production,[50] and soy protein and by-products such as okara and soy milk residue are being developed into biodegradable packaging and eco-friendly adhesives in the food and environmental materials industries.[51]

With the diversification of global soybean consumption, the nature of demand is transitioning from volume oriented to quality oriented. For example, the European market exhibits a strong preference for soybeans that are non-genetically modified organisms and certified sustainable. Despite this, regional markets are exhibiting differentiated preferences for soybean quality. In sub-Saharan Africa, grain size and oil content have become key pricing factors in trade, as larger grains yield more oil and meal per unit weight and are therefore more profitable for processors and feed manufacturers.[52]

Global supply chains and logistics. The global soybean trade is highly dependent on complex, transboundary supply chains and logistics networks, whose efficiency and resilience are critical in determining trade patterns and their evolution (Figure 2). From production zones to final consumption markets, soybeans pass through multiple stages, including roads, rail, inland waterways, maritime shipping, port handling, and storage. A bottleneck in any of these stages can lead to widespread trade disruptions and rising costs.[59] For example, Brazil's export logistics system illustrates persistent structural challenges, although it is the world's largest soybean exporter. Over 60% of Brazil's soybeans are transported by truck over hundreds of kilometers from inland production areas such as Mato Grosso to coastal ports. Due to poor road conditions and travel disruptions during rainy periods, transportation costs have historically accounted for more than 28% of the soybean "free on board" price; i.e., the price at the port of shipment excluding freight.[60] Recently, the Brazilian government has promoted the development of intermodal systems combining rail and inland waterways, mitigating southern port bottlenecks by enhancing northern export corridors, including the terminals along the Tapajós River (Port of Itaituba-Miritituba and Santarem).[61] In contrast, the United States relies on an efficient intermodal network that connects major soybean-producing areas in the Midwest with ports like New Orleans via the Mississippi River and railroads, a system that underpins its export competitiveness.[62]

Port infrastructure capacity also has a profound impact on soybean trade efficiency. In an empirical study on port efficiency and trade flows in the United States and globally, Blonigen and Wilson[63] found that a 10% improvement in port efficiency could result in approximately 3.2% trade growth. During peak export seasons, the probability of port congestion rises significantly, particularly in countries with underdeveloped infrastructure. At Brazil's Santos and Paranaguá ports, vessel wait times often exceed 2 weeks, which increased delivery uncertainties and surged international freight rates.[64] Argentina has long faced challenges such as insufficient rail connectivity and fluctuating inland waterway levels, which limit port throughput and indirectly erode Argentina's pricing power and bargaining position in global markets.[65] Miller and Hyodo[66] further identified that the number of berths, ship-to-shore gantry crane density, and automation levels are key indicators of the bulk cargo handling capacity at Latin American ports. By contrast, well-developed United States ports, such as New Orleans, exhibit superior ship-loading efficiency and logistics coordination, which significantly enhance delivery reliability. Storage infrastructure also plays a pivotal role in ensuring supply chain stability. Lima et al.[67] found that harvesting soybeans at 23% moisture content, drying to 11% using low-temperature drying at 80°C, and then storing below 23°C effectively preserves oil and protein stability, thereby minimizing trade losses caused by quality deterioration. The USDA[68] also recommends scientific drying and sealing technologies to keep storage loss rates below 1.5%, making them especially suitable for export-oriented inventory management.

With technological advancements, digital tools are increasingly being applied in soybean supply chain management, enabling better handling of logistics complexity and improving trade transparency. Blockchain technology is being used to build traceability systems that ensure end-to-end transparency from production sites to end markets, improving buyer confidence in product origin and sustainability certifications.[69,70] Internet of Things (IoT) devices enable real-time monitoring of temperature and humidity during transportation, helping prevent product spoilage and delivery disruptions.[71] AI and machine learning have demonstrated significant advantages in demand forecasting and route optimization. For example, by predicting dynamic variables such as port congestion, weather changes, and traffic incidents, they can enhance scheduling and warehousing efficiency while improving overall system resilience.[72,73]

In the context of intensifying extreme weather events and growing geopolitical instability, building digitally resilient supply chain systems has become more urgent than ever. Moreover, geopolitical conflicts and trade wars have imposed shifting demands on logistics systems. During the United States-China trade war, for instance, China rapidly adjusted its import sources from the United States to Brazil and Argentina, placing immense pressure on the latter's port and transportation infrastructure and accelerating their investment in logistics capacity.[74] These trends demonstrate that supply chain efficiency not only determines the effectiveness of transportation but also directly shapes the export competitiveness of producing countries and the strategic security perceptions of importing nations.

Price volatility in the soybean trade. Price volatility is a critical force shaping the global soybean trade landscape, particularly in the face of recurring global economic shocks and the increasing frequency of extreme climate events (Figure 2). Historically, the main drivers of soybean price fluctuations include supply-demand imbalances, geopolitical events, and yield loss due to climate or natural disasters.[75–77] At the same time, the global soybean pricing system further exacerbated the effects of price fluctuations on trade flows. Although Brazil overtook the United States as the world's largest soybean exporter in 2012, international soybean prices are still largely dictated by the Chicago Board of Trade (CBOT) in the United States.[78,79] This pricing system is rooted in a basis trading model established in the mid-20th century, where spot prices are determined by future prices plus a premium or discount. It renders global soybean trade highly sensitive to market signals from the United States, though it helps mitigate certain pricing risks.[80] In addition, major importers, such as China, have limited leverage over global soybean price-setting mechanisms.[81]

The reconfiguration of global trade patterns induced by soybean price volatility has been well documented by numerous studies and case analyses.[20,82,83] During periods of price surges, importers often diversify their supply sources to reduce dependency on specific exporters. For example, the 2012 United States drought substantially reduced soybean production (and exports) in the United States and prompted China to shift soybean purchases toward Brazil,[84] thereby initiating a long-term trend that established Brazil as China's primary supplier.[85] In contrast, during price downturns, exporters are pressured by shrinking profit margin erosion and accumulating unsold inventories. Argentina in 2018 serves as a notable case; while currency depreciation enhanced its export competitiveness, concurrent declines in soybean production and fluctuations in global demand exacerbated fiscal deficits and deepened its economic crisis.[86] Southeast Asian countries reduced their reliance on single-source soybean supplies during the 2007–2008 global food price crisis by adopting diversified procurement strategies.[87] In contrast, African nations, limited by fiscal capacity, tended to switch to lower-cost substitute crops in response to price hikes. These events demonstrate that price volatility in soybean not only influences spot transactions but also deeply reshapes global trade structures, bilateral agreements, and strategic stockpiling mechanisms in importing countries.

Frequent and sharp fluctuations in soybean prices have become a destabilizing factor in global trade, reshaping supply flows and amplifying vulnerabilities in both exporting and importing countries. During the 2007–2008 global food price crisis, surging soybean prices disrupted trade and exposed the fragility of international supply chains.[88] Import-dependent countries, particularly in the Global South, faced rising procurement costs and growing food insecurity. The structural exposure to international pricing mechanisms has also limited the ability of some countries to shield domestic markets. Indonesia's price stabilization efforts, for example, failed to protect either consumers or producers due to its reliance on imported soybeans and lack of domestic buffer capacity.[85] Volatility further undermines trade planning by deterring investment and increasing supply chain risk. Even financial hedging instruments have shown weaknesses under geopolitical stress. During the United States-China trade war, the price discovery function of the CBOT was significantly weakened, revealing that traditional futures markets may not effectively manage risks under structurally driven shocks.[81]

Indirect drivers of soybean trade

Production factors and technological advancement. The geographical patterns and trade routes of global soybean flows are also driven by production factors and rapid technological innovation (Figure 2). The evolution from a United States-dominated export structure to a multi-nodal trade network centered around Brazil, Argentina, and China reflects deeper structural dynamics, including differences in land availability, climate suitability, labor costs, and levels of mechanization as well as the widespread adoption of biotechnologies, precision agriculture, and agricultural automation.[89–91] Land abundance and favorable climatic conditions form the foundation for production expansion. For instance, Brazil has emerged as the world's leading soybean exporter thanks to its abundant arable land and tropical climate.[92] Guilpart et al.[93] employed machine learning to analyze the relationship between climate and soybean yields, highlighting significant opportunities to improve soybean self-sufficiency in Europe under both historical and projected climate scenarios. In contrast, despite the fertile soils of northeastern China's Heilongjiang Province, limited market incentives and insufficient investment in technology have restricted production, largely due to land use competition with corn.[94,95] Additionally, the increasing frequency of extreme weather events linked to climate change presents critical challenges to soybean productivity. In the United States Midwest, for example, droughts and heavy rainfall have caused yield losses ranging from 5% to 22%,[96] while projections for northeastern China suggest a potential decline of up to 4.2% under climate change projections with high-emission scenarios.[97] Consequently farmers are increasingly turning to climate-adaptive strategies, including adjustment of sowing schedules and development of stress-tolerant cultivars.[98,99]

Agricultural inputs such as improved seed varieties, fertilizers, pesticides, and irrigation systems play a central role in shaping soybean supply and cost structures. Their availability and affordability directly affect yield, production efficiency, and trade competitiveness.[100–102] For example, the adoption of drought-tolerant or pest-resistant cultivars may improve productivity in climate-vulnerable regions, helping stabilize output and trade volumes.[103] Among the key external factors influencing input costs, global energy prices, especially oil, exert a substantial indirect impact on soybean trade. Oil prices affect the cost of producing and transporting fertilizers, fueling machinery, and operating irrigation systems. High energy prices can significantly raise production expenses, discourage planting in cost-sensitive regions, and reduce exportable surpluses.[104] In addition, beginning in the mid-2000s, the rise of the biofuels industry, driven by policies like the United States Renewable Fuel Standard, strengthened the link between oil prices and agricultural commodities, including soybean oil. As crude oil prices rise, demand for soy-based biodiesel increases, creating upward pressure on soybean prices and influencing global trade flows.[105] These input-driven cost dynamics ultimately influence soybean prices, trade margins, and feed affordability.

Beyond these foundational factors, the agricultural technology revolution is rapidly reshaping the global soybean supply-demand landscape. The widespread application of genetically modified (GM) varieties, especially those resistant to herbicides and pests, has significantly improved production efficiency while lowering labor and chemical input costs.[106] GM soybeans now dominate production in the United States, Brazil, and Argentina and, when combined with mechanized farming systems, have markedly increased yield and enhanced operational efficiency.[15] GM soybean traits such as glyphosate tolerance and insect resistance have reduced pesticide use by 10%–20% and improved yields by over 5%.[107] Despite these advantages, the adoption of GM soybeans remains controversial. While offering agronomic and economic benefits, GM crops have raised concerns about environmental and health risks, leading major importers such as the EU and Japan to enforce strict regulations based on precautionary principles.[108–110] In contrast, precision agriculture has gained broader international traction due to its adaptability across diverse farming contexts. By integrating drones, soil sensors, and Global Positioning System (GPS)-guided automation, producers have improved input efficiency and sustainability. Weed detection in soybean fields reached over 98% accuracy using deep learning, enabling precise herbicide application and improved yield management,[111] while long range-based soil monitoring networks have enabled precise irrigation in remote regions.[112] These innovations allow producers to better respond to market fluctuations, enhance product consistency, and strengthen global competitiveness. In parallel, advances in animal nutrition have also begun to reshape soybean demand. Precision feed formulation now enables the use of low-protein diets supplemented with synthetic amino acids and alternative ingredients such as microalgae. These strategies maintain livestock performance while improving nitrogen efficiency and reducing dependence on soybean meal.[113–115] Though not yet widespread, such innovations could gradually lower soybean-based feed demand and alter global trade flows over time.

Disparities in mechanization levels also continue to shape global trade patterns. In the Americas, high capital investment and mature mechanization have enabled large-scale, cost-effective soybean farming. Conversely, reliance on manual labor in parts of Asia and Africa has resulted in lower productivity and slower adoption of advanced technologies. For example, the coordinated use of precision planters and combine harvesters in the United States and Brazil has significantly reduced labor inputs and improved profitability.[116,117] In India, mechanized sowing and harvesting have increased net soybean income by 11.7% while cutting seed and labor costs by 9.4% and 15.2%, respectively.[118] However, in China, limited use of dense planting machinery has contributed to rising production costs and suppressed yields, undermining domestic price competitiveness and increasing reliance on imports.[119] Nonetheless, on-site learning initiatives and technology extension programs for smallholders are beginning to lower adoption barriers and promote smart agriculture transitions in many developing countries.[120] Looking ahead, the integration of mechanization with digital technologies such as the IoT and machine vision is expected to optimize planting decisions and enhance harvest precision, acting as a critical catalyst for the "technology-efficiency-profitability" cycle in the global soybean trade. Ultimately, shifts in production conditions and technological capability not only determine supply potential and cost structures but may also influence comparative advantages in global trade and contribute to the transition toward more sustainable agricultural models.

Policy instruments and trade barriers. The structure and direction of the global soybean trade are deeply shaped by policy instruments and trade barriers (Figure 2). Major producing and consuming countries have systematically reshaped global soybean trade patterns through tools such as agricultural subsidies, tariff policies, technical regulations, and bilateral or multilateral trade agreements. These policy instruments function not only as essential tools for domestic market regulation but are also increasingly central to international competition and strategic positioning.

First, agricultural subsidy policies are widely employed by exporting countries to enhance international competitiveness. In the United States, the USDA Farm Bill Price Loss Coverage program and the Risk Management Agency crop insurance subsidies program provide robust income protection for soybean producers. Data show that such mechanisms have increased planting returns by approximately 37%, driving the continued expansion of soybean acreage.[121,122] In contrast, Brazil has adopted a more market-oriented approach to soybean incentives, utilizing production credit and export tax rebate systems.[123] By linking fiscal incentives to environmental compliance through "green subsidies," Brazil has enhanced the sustainability credentials of its exports and secured premium pricing in high-end markets such as the European Union. The Chinese government has supported domestic soybean production through temporary stockpiling policies, target price mechanisms, and producer subsidies, indirectly influencing the structure of its import demand.[124] Agricultural subsidy policies have not only shaped global soybean production patterns but also triggered international trade disputes. For example, the United States' subsidy programs were challenged by Brazil at the World Trade Organization (WTO), which claimed that these policies violated fair trade principles and harmed the export interests of other countries.[125]

Tariff and quota policies play a decisive role in trade barriers and market structure. In 2018, China's imposition of a 25% tariff on United States soybeans led United States exports to drop from approximately 30 million tons in 2017 to 16.64 million tons, a 49% reduction, puncturing America's share of China's market. Brazil swiftly filled the gap, increasing its share of Chinese imports from 53% in 2017 to 78% by 2019.[56] Argentina also illustrates how trade policies shape soybean export patterns. Since 2002, high export taxes that reached 44.1% in 2008 have curbed raw soybean exports but promoted processed products like soybean meal, which exceeded 70% of related exports. However, the policy also limited farm income and slowed planting expansion before 2015.[126] When Argentina imposed a temporary 23% export tax in 2023, Chinese importers responded by raising their purchases from Brazil by 15% within 3 months.[127] In April 2025, renewed United States-China trade tensions led to a 4% annual decline in United States soybean acreage, with the USDA projecting exports to China to fall to just 15%.[18] Simultaneously, CBOT soybean futures fell below $10 per bushel, marking a 4-year low. Although tariffs are powerful short-term tools for adjusting trade flows, the resulting realignments may destabilize supply chains, especially when multiple countries simultaneously revise export taxes, thereby exacerbating volatility in global markets. Beyond these immediate disruptions, recurring United States-China frictions are also catalyzing long-term structural shifts. In particular, China and other major importers are accelerating diversification strategies, increasingly exploring emerging suppliers in regions such as sub-Saharan Africa.[128] These moves reflect a broader reassessment of supply chain resilience under persistent geopolitical uncertainty. Meanwhile, regional trade agreements are increasingly reshaping global soybean flows through tariff reductions. Agreements such as the United States-Mexico-Canada Agreement and Comprehensive and Progressive Agreement for Trans-Pacific Partnership promote trade facilitation through zero tariffs and harmonized sanitary and phytosanitary standards, but they also create a dual-track system with liberalized trade within agreements and constraints outside them, thereby intensifying market segmentation.[129]

The proliferation of technical trade barriers has further heightened the complexity of the global soybean trade. Regulatory discrepancies ranging from GM crop approvals and pesticide residue limits to forest conservation standards have raised compliance costs and created implicit market entry barriers. For example, glyphosate remains widely used in Brazil, where over 90% of soybeans are glyphosate tolerant, but is restricted in China due to health and environmental concerns.[130] These differences complicate trade logistics and increase testing costs for exporters. Brazilian soybeans exported to the EU must meet strict residue and traceability requirements, contributing 12%–18% to total export costs.[131] Similarly, South Korea's 117 pesticide residue checks and China's quarantine regulations have significantly increased inspection times and United States export costs, reshaping trade flows and pricing structures.[132]

Climate stress and extreme events. In recent years, climate change has emerged as one of the most formidable indirect forces shaping global soybean trade (Figure 2). Rising temperatures, shifting precipitation patterns, and the increasing frequency of extreme weather events are altering production capacities in major soybean-producing countries and reshaping the landscape of international trade. Key producing regions, including the United States Midwest, Brazil's Cerrado and Amazon, and Argentina's Pampas, are confronting diverse climate-related impacts, such as prolonged droughts, heatwaves, and intense flooding. These conditions contribute not only to yield volatility[57] but also severely disrupt supply chain operations and export logistics. In the United States, for instance, heatwaves and soil moisture deficits in the Midwest have significantly shortened the soybean growing season, particularly affecting yields during the flowering and pod-filling stages.[133,134] In Brazil, intensifying deforestation has exacerbated drought trends in the Amazon and Cerrado regions; it delays onset of the agricultural rainy season by an average of 36 days since the 1980s, reduces total precipitation by 36.7%,[135] and thus narrows planting windows and compromises the stability of production systems.[136,137] At the same time, this impact disrupts the double-cropping system, resulting in an overall decrease in land use efficiency, which indirectly restricts soybean production.[138,139] Research by Hamed et al.[31] estimates that approximately 30% of the global soybean yield gap in 2012 could be attributed to anthropogenic climate change. The region-specific nature of these climate risks has prompted importing countries such as China and the European Union to reassess their reliance on high-risk supply sources.[140]

Extreme weather events also pose significant threats to the soybean supply chain. Droughts and floods not only impede crop development but also exacerbate the vulnerability of infrastructure and logistics systems. For example, floods in Argentina in 2023 paralyzed 30% of the country's soybean export corridors, triggering a 12% spike in international prices.[141] In Central and South America, transportation disruptions such as port closures and road damage have amplified supply-demand imbalances, causing severe disruptions for soybean-importing nations.[142] Moreover, while elevated atmospheric CO_2 concentrations can enhance photosynthetic efficiency and biomass under certain conditions, this so-called "fertilization effect" is often offset by concurrent heat stress. Additionally, elevated CO_2 may reduce seed protein content and alter mineral composition, diminishing the feed and food value of soybeans.[143,144] Therefore, climate adaptation in soybean production must address not only yield stability but also evolving nutritional quality and trade demands.

In response to escalating climate risks, major producing countries are adopting a range of adaptation strategies. These include the development of drought- and flood-tolerant soybean varieties,[145,146] sensor-based technologies for precision irrigation and sowing schedule optimization, and agricultural practices aimed at enhancing soil health.[147] Policy measures have also played a pivotal role. In the United States, the Environmental Quality Incentives Program provides financial support for the adoption of climate-smart practices, while Brazil's Low-Carbon Agriculture Plan Plus program encourages investments in conservation tillage and irrigation systems.[148] In addition, risk management tools, such as climate index insurance and adaptive provisions in trade agreements, are increasingly being incorporated into multilateral frameworks to mitigate climate-induced production and trade volatility.[149,150] However, the adoption of such technical and policy measures remains limited among smallholder farmers, underscoring the necessity of participatory local training initiatives and targeted financial assistance. Ultimately, the sustainable development of the global soybean trade system will hinge on regionally coordinated adaptation strategies, enhanced infrastructure resilience, and policy alignment grounded in principles of climate justice.

Other socioeconomic and biological shocks. In addition to conventional drivers, emerging socioeconomic and biological shocks, such as the COVID-19 pandemic and the Russia-Ukraine war, have added new layers of volatility and systemic risk to the global soybean trade.

The COVID-19 pandemic severely disrupted Brazil's soybean supply chain. Labor shortages, port congestion, and delayed input delivery, compounded by drought, led to a 10.5% decline in national soybean production in the 2020–2021 season, representing the sharpest drop since 1990.[58] Lockdowns and global logistical paralysis exposed structural fragilities in Brazil's production system. Between 2018 and 2021, fixed and variable production costs rose by 31% and 24%, respectively, while seed prices increased by 29%, largely due to global supply shocks and currency depreciation.[151] These dual financial pressures resulting from prior-season yield losses and historically high production costs in 2021–2022 highlight the vulnerability of Brazil's soybean production

Figure 3. Environmental and social impacts of the global soybean trade The green box shows the historical deforestation areas caused by soybean expansion from 2001 to 2019 and the projected future deforestation areas from 2019 to 2035, with data sourced from Song et al.[4] and Marin et al.[172] The orange box displays the soybean output values in 1991 and 2023, along with the projected production value for 2035, based on data from FAO[3] and IndexBox.[185]

system and, by extension, the fragility of the international soybean trade under compound shocks. At the trade level, the pandemic intensified the linkage between Brazil's spot prices and international soybean futures, reinforcing Brazil's growing influence in global grain price formation.[152] Simultaneously, export redirection toward import-stressed markets, such as the United Kingdom, increased by nearly 50%, while domestic consumer food prices rose by 60%.[153]

In parallel, the Russia-Ukraine war introduced further disruptions. Brazil imports over 85% of its fertilizers, with 36% of potassium sourced from Russia and Belarus in 2015.[154] The war, along with international sanctions and Russia's self-imposed fertilizer export restrictions,[155] disrupted this critical input supply, leading to sharp price increases and threatening long-term soil fertility and yield stability.[156,157] Meanwhile, Ukraine's soybean output dropped significantly due to war-related planting and transport challenges, further straining global oilseed supply chains.[158] Together, these compounded shocks underscore the fragility of global agricultural trade under interconnected geopolitical and biological stressors.[159]

ECOLOGICAL AND SOCIAL IMPACTS OF GLOBAL SOYBEAN TRADE DYNAMICS

The global soybean trade has profoundly reshaped ecological systems and socio-economic structures worldwide. Evolving soybean trade patterns have driven the continual expansion of cultivation areas across multiple continents, substantially intensifying land use and exerting increasing pressure on natural resources. This trend has raised widespread concerns over ecosystem degradation and the unsustainable exploitation of environmental assets.[160–164] Concurrently, the development of the global soybean trade generates multifaceted socio-economic feedbacks, directly impacting key issues such as regional development and food security.[160,162,165,166] A systematic understanding of the ecological and social implications of the global soybean trade is crucial for the development of sustainable agricultural governance frameworks and forms a necessary foundation for advancing key United Nations Sustainable Development Goals (SDGs), including "Climate Action," "Zero Hunger," and "Life on Land."[161,164,167]

Environmental impacts

Deforestation and biodiversity loss. The rapid expansion of the global soybean trade has had profound impacts on forest ecosystems and carbon emission patterns, particularly in regions where primary forests or tropical savannas have been converted into soybean croplands (Figure 3). This land conversion has led to a sharp decline in ecosystem carbon stocks and makes it a significant source of greenhouse gas emissions.[168] In biodiversity-rich regions, such as the Amazon and Cerrado, soybean cultivation has emerged as a primary driver of land use change (LUC).[169] Between 2000 and 2019, nearly half of the soybean expansion in South America occurred within the Cerrado biome.[4] During the same period, approximately 8.4 million hectares of forest were lost in Cerrado, with around 10% (840,000 ha) converted into soybean fields. Across South America, soybean expansion was responsible for an estimated 6.3 million hectares of deforestation (Figure 3), either directly or indirectly.[4] Converting mature rainforest to cropland is estimated to result in carbon stock losses of approximately 176.61 million kJ/ha.[170] In 2019, greenhouse gas emissions related to soybean production were estimated at 0.6 Gt CO_2-equiv, primarily driven by deforestation and fertilizer use in South America. As an exporter, Brazil's soybean shipments in that year accounted for 196 Mt CO_2-equiv emissions. As an importer, China's soybean imports were responsible for 319 Mt CO_2-equiv emissions, representing 46% of its total import-related emissions.[171] The conversion of forests into soybean croplands not only releases vast quantities of CO_2 but also diminishes the role of forests as global carbon sinks, directly challenging the core objectives of SDG 13 (Climate Action) and SDG 15 (Life on Land). According to Marin et al.,[172] if current expansion trends persist, then soybean production will require an additional 5.7 million ha of cropland, mostly at the expense of forests and grasslands, by 2035 (Figure 3), leading to 1,955 Mt of CO_2 emissions.

Soybean-driven deforestation is not limited to direct land clearing; it also encompasses indirect deforestation arising from land substitution between pasture and crop production, triggering cascading land use transformations.[4,173] In Mato Grosso, Brazil, soybean production exhibits both intra-regional and peri-regional coupling effects, where economic gains concentrated in core urban centers are often accompanied by deforestation and ecological degradation in adjacent rural areas.[174] This spatial mismatch between economic benefits and environmental costs complicates sustainability efforts, as local policies often fail to consider cross-boundary ecological impacts. Notably, soybeans grown for domestic markets tend to have a stronger link to deforestation than those cultivated for export.[175] This underscores the importance of implementing robust supply chain transparency mechanisms and international trade policies aimed at mitigating the effects of indirect LUC and ensuring that sustainability commitments yield a measurable environmental footprint.

In terms of policy responses, various governance mechanisms have been introduced globally to curb deforestation associated with soybean expansion. In the Brazilian Amazon, the Soy Moratorium, enacted in 2006, led to a 57% reduction in soybean-related direct deforestation by 2015,[176] illustrating the potential effectiveness of targeted policy interventions. However, the effectiveness of such policies varies considerably across regions.[135,177,178] Although temporary reductions in forest loss have been achieved in some municipalities through satellite-based monitoring,[9,179] the overall efficacy of these measures appears to be diminishing. Moreover, the policy's narrow focus on soybeans, excluding other land-intensive commodities such as corn, cotton, and beef, has encouraged land use substitution while placing disproportionate pressure on soybean farmers. This highlights the risks posed by fragmented governance and the externalization of ecological responsibilities, emphasizing the need to establish multi-level coordination frameworks that operate across local, national, and international scales.

Another major consequence of tropical deforestation linked to soybean expansion is biodiversity loss, which is particularly severe in ecologically valuable areas such as the Amazon, Cerrado, and Gran Chaco. Large-scale conversion of native forests and grasslands into soybean fields not only destroys critical habitats but also fragments ecosystems, intensifies edge effects, and increases human disturbances. These factors collectively undermine ecological network structures and reduce the stability and resilience of ecosystems.[180] In the Cerrado, countryside species-area relationship assessments indicate that, as of 2021, approximately 98% of potential species loss can be attributed to agricultural land use.[180] The ecological disruption caused by soybean expansion extends beyond habitat loss by altering ecosystem processes and interspecies interaction networks. Studies have shown that even modest reductions in habitat area can disrupt over 10% of key ecological interactions, leading to population isolation and the degradation of ecosystem functions.[181] This poses a particular threat to narrowly endemic species with limited geographic distributions, as more than 85% of micro-endemic plants are currently on the brink of extinction under prevailing trends.[182] Moreover, the monocultural nature of soybean cultivation degrades the quality of the ecological matrix, thereby reducing the functionality of ecological corridors and constraining species migration. Ramírez-Delgado et al.[183] emphasize that matrix fragmentation and the intensity of human intervention are more accurate predictors of species extinction risks than forest area loss alone. In the Gran Chaco region, the distribution of large mammal populations has already been affected by soybean expansion,[184] while essential ecological processes such as pollination and seed dispersal have been disrupted in cascading ways.

Land degradation and water resource depletion. The environmental repercussions of the global soybean trade also include soil system stability and water security, both of which are fundamental to agricultural sustainability (Figure 3). In Brazil's Mato Grosso state, the conversion of forests into soybean and cotton cultivation systems has triggered severe soil erosion; for instance, in the Curisevo River Basin, annual erosion rates have reached as much as 134,526 tons per hectare.[186] While soybean cultivation can offer localized improvements in soil nutrients through nitrogen fixation, these benefits are negligible when compared to the long-term losses in carbon stocks and degradation of ecosystem services resulting from deforestation.[170] In the Gurupi River basin, the economic losses linked to ecosystem service degradation due to agricultural expansion have been estimated to exceed $1.961 billion.[177] Moreover, the impacts of monoculture systems on soil structure are particularly severe. In the absence of effective crop rotation and nutrient replenishment strategies, continuous extraction of key elements such as nitrogen has led to growing dependence on fertilizers, triggering cascading effects such as soil acidification and the reconstruction of microbial communities.[187,188] Continuous soybean monoculture contributes to soil degradation by lowering nutrient use efficiency and increasing phosphorus occlusion and erosion risk. For instance, rotational systems in Mato Grosso showed 20%–45% higher nutrient efficiency than monoculture systems.[189] In addition, land-use change from native Cerrado vegetation to continuous soybean production has been shown to significantly reduce infiltration rates and aggregate stability, making cropland soils more susceptible to erosion and nutrient leaching.[190] Sparse early canopy cover and conventional tillage practices further expose soil surfaces, increasing susceptibility to rain-induced erosion, especially in tropical regions with heavy rainfall. As a result, tropical regions producing soybeans experience topsoil loss at rates two to three times higher than those under diversified cropping systems.

Water resource pressures (e.g., both quantity and quality) are likewise intensifying. In South American river basins, runoff from soybean fields laden with agrochemicals and nutrients has exacerbated both surface and groundwater pollution, disrupting regional aquatic ecosystems.[191,192] In the United States Midwest, intensive irrigation has contributed to declines in critical water reserves, including the Mississippi River alluvial aquifer.[193] Similar pressures are evident in the Colorado River Basin, where persistent drought and rising demand from agricultural and urban users have led to historically low reservoir levels and growing tensions over water allocations across states.[194] A regional survey revealed that 52% of local farmers attributed groundwater depletion to agricultural water use, and more than half regarded poor water management as a more pressing issue than absolute water scarcity. Soybean irrigation costs, ranging from $399 to $615 per hectare, incentivize high-intensity irrigation practices that further exacerbate aquifer overextraction. Comparable challenges are evident in arid areas such as the Texas High Plains, where long-term dependence on the Ogallala Aquifer for irrigated soybean production is now jeopardizing regional water security.[195] Mitigation strategies, such as substituting water-efficient crops, implementing dryland rotations involving soybean and sorghum, and adopting integrated water management systems, have demonstrated promising potential for water conservation. For instance, fallowing combined with managed aquifer recharge has been shown to increase aquifer recovery rates by up to 31 mm per year.[196] However, widespread adoption of these conservation measures remains hindered by the prevailing economic reliance on high-input irrigated crops.

Socioeconomic impacts

Agricultural economy and income distribution. The expansion of the global soybean trade has triggered transformations in the agricultural economies of major exporting countries, particularly in South America, most notably Brazil and Argentina (Figure 3). Through the development of soybean-related industrial chains, these countries have achieved rapid agricultural growth. Brazil's soybean export value surged from $2.7 billion in 2000 to $43 billion in 2024, raising its global market share to 54%.[17] In 2023, soybeans and their derivatives (soybean meal and oil) accounted for 21.6% of Argentina's total exports, with as much as 91.4% of soybean exports destined for China.[3] The global soybean production value increased from $21.1 billion in 1991 to $195.3 billion in 2023,[3] and it is projected to reach $233.4 billion by 2035.[185] As a labor-intensive sector, soybean cultivation has directly contributed to employment growth in agriculture, processing, and logistics, particularly in rural, agriculture-dependent regions, where it plays a role in poverty reduction and the improvement of household living standards.[197] Furthermore, soybean trade has stimulated infrastructure development such as road networks, storage facilities, and processing plants, thereby enhancing agricultural productivity and market connectivity.[198] These upgrades have, over the long term, supported income stabilization and institutional resilience.

Despite its contributions to agricultural expansion and value chain development, the soybean trade has also introduced several social challenges. In major exporting countries, such as Brazil and Argentina, intensified industrialization and mechanization have reduced the demand for traditional agricultural labor while increasing the need for technically skilled workers.[199] The capital-intensive, large-scale nature of soybean cultivation has concentrated land ownership among large agribusinesses. Smallholder farmers have faced mounting challenges, including land consolidation, rising input costs, and exclusion from competitive markets, leading to their gradual exit from production systems.[200] In Argentina, farms exceeding 500 ha, which constitute just 6% of all farms, produced 50% of the country's soybeans, while 73% of smallholders were pushed out of the market. Similarly, in Brazil, farms larger than 500 ha accounted for 67% of soybean production, and the share of farmers with holdings smaller than 50 ha declined from 52% in 1985 to 23% in 2017.[201] These shifts have intensified rural social stratification and eroded the diversity of traditional crop and livestock systems.[16,202] Meanwhile, urban centers have increasingly become focal points in the soybean value chain, attracting significant investment and fostering the growth of processing, packaging, logistics, and retail sectors, thereby accelerating broader industrialization.[203] However, this trend toward urbanization has placed growing demands on infrastructure and public services, especially amid low-income urban expansion and the proliferation of informal employment.[204] In addition, the dominance of soybeans in national agricultural structures has heightened economic dependency on external markets, rendering exporting countries more susceptible to global price fluctuations, exchange rate volatility, and shifts in trade policy.[205]

The evolution of the global soybean trade has produced uneven economic impacts across countries and regions. In major exporting countries, such as Brazil, the United States, and Argentina, rising global demand for soybeans has boosted agricultural gross domestic product and stimulated related industries, including port infrastructure, logistics, and processing.[174] Conversely, in major importing countries, such as China and the European Union, high reliance on soybean imports has also generated regional economic repercussions. In China, where approximately 85% of soybean consumption depends on imports, this dependence has reshaped local economies, particularly in traditional soybean-producing regions such as the northeast. The influx of cheaper soybeans from Brazil and the United States has eroded the competitiveness of domestic producers and led to a 25% decline in China's soybean planting area between 2004 and 2016, with much of the land repurposed for corn and rice cultivation.[206] Despite interventions such as the Soybean Producer Subsidy Program, many farmers have shifted toward more profitable crops, resulting in a further 27.9% decline in soybean acreage in northeast China between 2017 and 2021.[207] Trade policy shifts have further exacerbated cross-border economic disparities. During the 2018 United States-China trade war, tariff adjustments directly harmed United States soybean producers. United States exports to China plummeted, leading to estimated income losses of $4.9 billion across several Midwestern agricultural states.[208,209] In contrast, surging demand bolstered Brazil's soybean export prices, further stimulating its agricultural economy.[83] These cross-border transmission effects not only underscore the complexity of the global soybean trade but also highlight the vulnerabilities and interdependencies of different countries and regions within global supply chains.[210] The dominance of transnational corporations in these supply chains has further exacerbated these disparities.

Global food security**.** As a critical pillar of modern agriculture and food systems, the global soybean trade has undergone structural transformations with far-reaching implications for food security worldwide (Figure 3). As one of the most important sources of plant-based protein and edible oil, soybeans underpin global food chains involving meat, dairy, and other essential products, playing a pivotal role in ensuring nutritional security across many countries.[211] At present, over 80% of global soybean exports (150 million tons) originate from just three countries—Brazil, the United States, and Argentina—while China, the European Union, and Southeast Asia represent the major import markets.[3] Within this highly concentrated supply chain structure, any disruption, whether due to climatic extremes, policy shifts, or logistical bottlenecks, can rapidly evolve into a global supply shock, jeopardizing food availability and price stability across multiple regions.[211–213] For example, the 2012 drought in the United States Midwest significantly reduced export capacity, triggering an over 30% surge in international soybean prices.[77] Similarly, the 2018 United States-China trade war led to a sharp increase in Brazil's soybean exports, pushing export prices up by approximately 50% year-on-year,[214] while domestic feed and meat prices in China saw modest but noticeable increases.[215,216] These cross-border trade shocks not only affect supply dynamics in importing countries but also ripple through feed chains to influence livestock and food processing industries, thereby posing broad threats to agricultural stability and food security. Furthermore, speculative capital activity in agricultural futures markets has amplified the volatility of such an impact on global food security.[75,80]

In import-dependent countries, changes in soybean trade primarily affect food security along two key dimensions: availability and accessibility. First, supply chain disruptions drive up animal feed prices, which subsequently increase the costs of meat, dairy, and vegetable oil products, thereby undermining food affordability and nutritional intake among low- and middle-income populations.[217,218] In response to these vulnerabilities, China has promoted domestic soybean cultivation and initiated agricultural transitions in the northeast and Huang-Huai-Hai regions. However, even under the most optimistic scenarios, self-sufficiency is projected to remain below 25% by 2030.[219] Second, the imbalanced allocation of soybean utilization intensifies risks to nutritional accessibility. A significant portion of global soybean output is allocated to livestock feed and biofuel production rather than direct human consumption. During periods of supply stress, this structural allocation exacerbates the unequal distribution of plant-based protein and undermines per capita nutritional intake in developing countries that heavily rely on such sources.[211] At the same time, while emerging markets, such as those in Africa, hold potential for soybean production, weak infrastructure and climate vulnerability have hindered local expansion, thereby sustaining import dependence and increasing exposure to global trade fluctuations.[220] In summary, the concentration of both soybean trade flows and pricing capability not only heightens volatility in global food supply chains but also deepens inequalities in food access within and across nations, which poses significant risks to foundational food security systems.

Addressing the food security risks associated with global soybean trade requires coordinated efforts in both supply chain resilience and institutional innovation. On one hand, enhancing the diversification of supply sources and cultivating complementary trade partnerships at the global level are critical to reducing reliance on a limited number of exporters and improving risk management capacity.[216] On the other hand, importing countries should strengthen domestic agricultural infrastructure and promote sustainable soybean production through the advancement of technologies and farming practices. The adoption of digital tools, such as blockchain and IoT, can also improve supply chain transparency and responsiveness during emergencies.[221,222] Additionally, reforming global agricultural pricing mechanisms to promote greater equity and transparency would enhance both the fairness and resilience of food systems. Looking ahead, global food governance should prioritize the integrated coordination of trade, finance, and nutrition security, ensuring that food systems remain inclusive, stable, and sustainable in the face of growing global uncertainty.

SUSTAINABLE DEVELOPMENT OF THE GLOBAL SOYBEAN TRADE

Strategic pathways for sustainability

The global soybean trade is intricately linked to both food security and economic development while simultaneously posing substantial environmental and ecological risks. Achieving sustainability in this sector necessitates coordinated reforms spanning policy, industry, and technological domains.[223–225] In response to these challenges, we propose three mutually reinforcing pathways: policy instruments, technological innovation and diffusion, and corporate initiatives (Figure 4). Particular emphasis is placed on the role of multi-level interventions, such as transboundary certification schemes, enhanced supply chain transparency, and the adoption of precision agriculture in strengthening the long-term resilience and sustainability of global soybean trade systems.[223,226]

Legal framework: Trade agreement and policy instruments**.** Promoting a more controlled and sustainable trajectory for global soybean trade requires the establishment of multi-tiered, cross-regional policy frameworks that reconcile production objectives with conservation priorities, enhance system resilience, and mitigate the cascading impacts of unexpected events.[7,227,228] This section examines the roles of domestic regulations and international trade agreements not only in fostering responsible supply chains and reducing environmental degradation but also in safeguarding trade continuity amid geopolitical tensions, such as tariff disputes and sanctions.

Sustainable soybean trade depends on coordinated policies across producer and consumer countries that align agricultural development with forest conservation. Brazil, as the world's largest soybean exporter, has implemented several regulatory tools, such as the Forest Code, Rural Environmental Registry, protected area expansion, and the Soy Moratorium, which helped reduce Amazon deforestation by 84% in the mid-2000s[229,230] The Forest Code requires landowners in the Amazon to retain 80% native vegetation, backed by penalties.[178,231–233] However, these protections do not extend uniformly to other critical ecosystems. Soybean cultivation has shifted to under-regulated frontiers like the Cerrado and the Chaco, where deforestation rates have been nearly double those in the Amazon.[24,234,235] Evidence of land use leakage[236] has fueled calls to extend moratoriums and enhance vegetation retention requirements, which currently stand at only 20%–35% in the Cerrado.[178] Policymakers are exploring incentive-based approaches such as compensation payments and credit restrictions.[235,237]

Consumer countries also shape sustainability outcomes. China, the world's top soybean importer, has shifted toward reduced soybean meal use in livestock feed to enhance food security and reduce deforestation-related imports.[10,238,239] Yet, such changes may displace environmental burdens to other sectors, such as palm oil production in Southeast Asia.[146,240] Cross-border coordination is essential to prevent such spillovers.[241,242] Trade tensions have

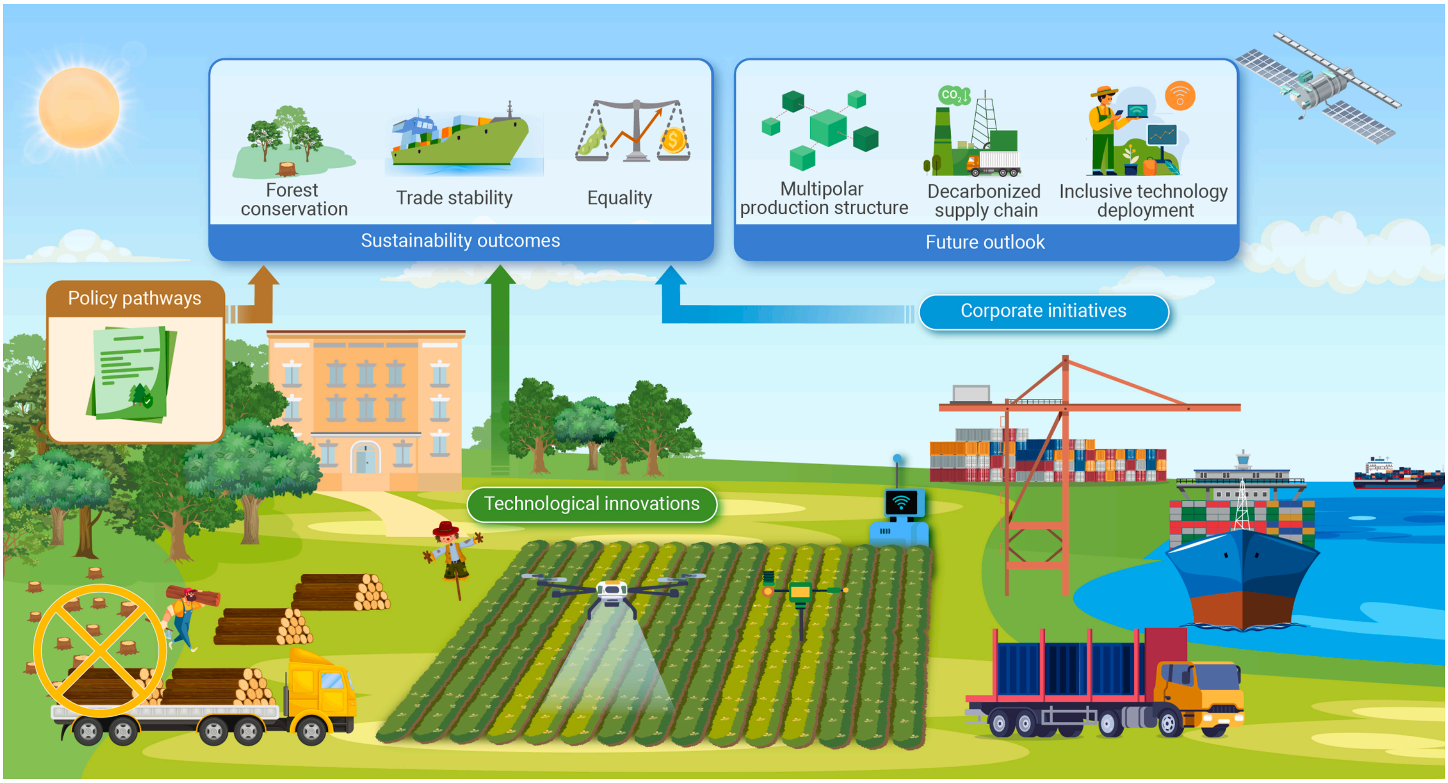

Figure 4. Sustainable development of the global soybean trade

also proven disruptive; during the 2018–2020 United States-China trade war, China's tariffs on United States soybeans led to increased sourcing from Brazil, spurring land use expansion and ecological pressure.[5,20] The renewed escalation of United States-China tensions in 2025 may again destabilize markets. On the demand side, new legal frameworks are emerging. The EU's 2023 Regulation on Deforestation-Free Products (EUDR) bans post-2020 deforestation-linked imports and requires full traceability for soybean and other high-risk commodities.[243] While it may drive upstream reforms, its stringent traceability rules disproportionately burden smallholders in producing countries, risking exclusion from EU markets and deepening rural inequality. The lack of global coordination also raises the risk of leakage, as unsustainable products may be redirected to less regulated markets like China.[33] Encouragingly, the China Oil and Foodstuffs Corporation has recently piloted deforestation-free soybean purchases using third-party certification.[244]

At the same time, legal and policy instruments play a vital role in safeguarding and promoting the soybean trade amid increasing geopolitical volatility. In the United States, tools such as the Market Facilitation Program exemplify how fiscal policy can buffer farmers against external shocks, particularly during tariff disputes. China, meanwhile, has adopted a strategy of import diversification, turning to Brazil, Argentina, and Russia to reduce reliance on any single exporter and insulate its supply chain from geopolitical volatility.[245] At the international level, institutions like the WTO offer a baseline legal framework through Most-Favored Nation rules and dispute resolution mechanisms. These help ensure fairness and predictability, allowing affected countries to contest discriminatory tariffs or trade barriers and defend their market access rights.

Beyond multilateral structures, bilateral and regional trade agreements further institutionalize cooperation and promote resilience. The Phase One United States-China Trade Agreement (2020) temporarily stabilized agricultural flows by committing China to $36.5 billion in annual United States farm imports, including soybeans, but also revealed the limitations of politically contingent deals.[246] In contrast, Brazil-China trade relations have pursued longer-term stability, supported by Chinese investments in Brazilian port and rail infrastructure to secure reliable exports.[8] Meanwhile, broader frameworks like Regional Comprehensive Economic Partnership and the EU-Southern Common Market agreement contribute by reducing tariffs, aligning technical standards, and embedding sustainability requirements.[247] As environmental standards tighten, exemplified by the EU's deforestation-free product regulation, exporting countries are being incentivized to upgrade land governance and traceability systems to maintain access to high-value markets. Together, these legal and policy instruments not only safeguard the soybean trade against disruption, but actively shape a more transparent, diversified, and ecologically aligned global trading system.

Technological and agronomic innovation: Enhancing transparency and efficiency. Technological innovation has become a crucial driver for enhancing the sustainability of the global soybean trade. Systemic advances in transparency, traceability, and production efficiency are unlocking new opportunities to reconcile the inherent tensions between production expansion and ecological preservation, reinforce supply chain resilience, and support the long-term stability of international trade networks.

At the transparency level, high-resolution remote sensing technologies have reshaped land use monitoring paradigms.[248,249] In key producer countries such as Brazil and Argentina, efforts toward near real-time satellite monitoring have substantially curtailed the concealment of illegal deforestation activities.[250–252] Monitoring systems like Brazil's Project for Monitoring Deforestation in the Legal Amazon (PRODES) and Real-Time Deforestation Detection System (DETER), managed by the National Institute for Space Research, alongside platforms such as Global Forest Watch and Trase, have enabled precise spatial linkage between land use changes and trade flows.[253] This integration of spatial and trade data has empowered firms to identify high-risk suppliers and facilitated risk-based procurement strategies in importing countries, marking a shift from conceptual frameworks toward the operationalization of supply chain accountability.

Regarding traceability infrastructure, distributed ledger technologies are addressing limitations inherent in traditional certification schemes.[254,255] Amid complex, multilayered supply chains, blockchain provides tamper-proof verification of deforestation-free product claims. A notable example is the collaboration between Bunge and CP Foods, which employed blockchain to validate 185,000 tons of deforestation-free soybean meal, enabling consumers to verify compliance through QR code scans.[256] Although large-scale adoption remains challenged by technological and cost barriers, such pilot initiatives signal a transition from "paper-based assurances" to "digital evidence," establishing the foundational infrastructure necessary for compliance with transboundary regulations.[257,258]

More critically, on the production side, agronomic and digital innovation directly promote trade by boosting yield potential, resource efficiency, and regional self-sufficiency. In Brazil, the United States, and Argentina, tools like GPS-guided planting, variable-rate fertilization, and crop sensors are closing yield gaps and lowering input intensity.[259] These are increasingly integrated with conservation practices and advanced seed varieties that reduce land use pressure. Elsewhere, emerging producers such as India and Indonesia are leveraging IoT-enabled monitoring, smart irrigation, and agronomic extension to improve productivity and strengthen domestic trade flows.[260–262] In Northeast China, there is significant potential to increase soybean production, with yield improvements alone capable of boosting output by over 60%, allowing regional market demand to be met without expanding cropland.[263] Moreover, while climate change has both positive and negative effects on soybean yields in the region, enhancements in planting density, breeding, and cultivation systems can substantially raise productivity and offset climate-related risks.[264] In Central and Eastern Europe, technology demonstration platforms are reconnecting breeding science with field-scale application, reviving local soybean sectors and reducing import dependency.[265] Next-generation breakthroughs such as CRISPR-enabled breeding, multi-omics trait mapping, and AI-based yield modeling are accelerating the development of climate-resilient, high-quality soybean varieties tailored to diverse market preferences.[266] Modeling studies suggest that meeting Brazil's projected 2028 demand through cropland expansion alone would generate up to 2 billion metric tons of CO_2 emissions; by contrast, focusing on yield improvement and intensification could reduce emissions by up to 58%.[172] These insights underscore that agricultural innovation is not only an environmental necessity but a strategic lever for supporting sustainable, climate-aligned trade growth.

Despite these advances, key challenges remain. Remote sensing tools still struggle with mixed-cropping landscapes and smallholder plots.[267] Blockchain systems are not yet widely adopted across entire supply chains,[268] and many precision farming technologies remain cost-prohibitive for smallholders.[269] Addressing these barriers requires increased investment in north-south technology transfer, scalable infrastructure, and inclusive innovation frameworks. Only by embedding technological progress across the entire value chain, from farm to port, can soybean trade systems achieve long-term sustainability, equity, and resilience.

Corporate initiatives: Zero-deforestation commitments and certification schemes. Voluntary corporate initiatives have emerged as pivotal drivers in advancing the sustainability transition of global soybean supply chains.[223,226,270] In response to reputational risks and exposure to deforestation-related liabilities, multinational grain traders, food manufacturers, and retailers have adopted zero-deforestation commitments, aiming to decouple soybean sourcing from land conversion.[271,272] These initiatives frequently rely on third-party certification schemes such as the Round Table on Responsible Soy (RTRS) and collaborative industry platforms such as the Cerrado Manifesto. Such efforts underscore the potential of market-based mechanisms to reconcile resource efficiency, ecological integrity, and supply chain transparency.[273] For example, the Soft Commodities Forum, supported by the World Business Council for Sustainable Development, requires member companies to systematically disclose deforestation-related risks in high-priority sourcing regions and to reduce compliance costs through shared data systems.[274]

Since the early 2010s, corporate environmental responsibility has gained considerable momentum, particularly in the soybean sector, where zero-deforestation pledges have gradually evolved from aspirational statements into concrete actions.[275,276] Numerous transnational firms have endorsed international frameworks such as the New York Declaration on Forests, committing to eliminate deforestation from their supply chains by 2030.[6] These pledges are increasingly supported by procurement policies that define geographic and temporal sourcing restrictions by drawing from successful precedents in the Brazilian Amazon. Industry alliances have also worked to expand the scope of collective action. The Cerrado Manifesto, for instance, seeks to extend zero-deforestation measures to the underregulated Cerrado biome in Brazil by fostering joint commitments among buyers.[274]

Despite progress in corporate rhetoric, substantial implementation gaps persist. While some traders began restricting sourcing from the Cerrado region in the late 2010s, by 2017, only 47% of soy exports from the region were covered by zero-deforestation commitments, which is well below the nearly 90% achieved in the Amazon region. These gaps largely stem from the limited scope of traceability systems under the complexity of supply chains. Most corporate monitoring frameworks are restricted to direct suppliers, leaving soybeans that enter markets through intermediaries, such as grain silos and brokers, largely unmonitored.[277] In Mato Grosso, for example, studies indicate that approximately 34% of soybean exports are routed through indirect channels that escape corporate oversight.[23] As Lambin and Furumo[278] argue, governance interventions that fail to encompass all production zones and supply chain nodes risk displacing deforestation to poorly monitored areas. These blind spots allow companies to assert deforestation-free compliance without robust implementation, often through the use of ambiguous terminology, partial disclosure, or reliance on low-stringency certification schemes, thereby exacerbating the risk of greenwashing.

The international divergence in sustainability standards poses challenges for consistency and compliance in the global soybean trade. The European Union enforces stringent environmental requirements through certification schemes such as RTRS and International Sustainability and Carbon Certification (ISCC) and regulatory instruments such as the EUDR. In contrast, the market dominated by emerging markets, particularly China, continues to operate through conventional supply chains, with limited attention to environmental disclosure and deforestation accountability.[244] Such divergence could be further exacerbated by geopolitical dynamics. The 2018 United States-China trade war prompted China to redirect soybean imports from the United States to Brazil. In turn, United States producers, facing intensified competition, may have relaxed their adherence to zero-deforestation sourcing, traceability systems, and third-party verification. The renewed escalation of United States-China trade tensions in 2025 may further deepen this bifurcation. Addressing such a diverged governance landscape will require an inclusive and interoperable international cooperation framework underpinned by mutual recognition mechanisms, transparent data-sharing infrastructures, and equitable development incentives. Without such alignment, market segmentation threatens to undermine the collective effectiveness of global environmental governance.[279–281]

Future outlook

The sustainable development of the global soybean trade stands at a pivotal crossroads. While the expansion of soybean cultivation has contributed to food security and economic growth, it has also led to serious ecological costs, including deforestation, biodiversity loss, and increased carbon emissions. A durable balance between production and conservation requires moving beyond fragmented governance toward systemic, integrated solutions. Efforts such as Brazil's Soy Moratorium and the EUDR illustrate the potential of both domestic and market-based international regulations to guide supply chain reform. However, unilateral action often triggers leakage effects, shifting environmental pressure to less regulated regions. Similarly, while corporate zero-deforestation pledges are important, they remain unevenly implemented, especially in complex, multinational supply chains. Technological tools, such as satellite monitoring, blockchain traceability, and precision farming, enhance transparency and operational efficiency; however, without equitable access, especially for smallholders, they risk reinforcing structural inequalities.

Looking forward, technological innovation will be crucial to reshaping the sustainability landscape of the soybean trade. Innovations in genetics, climate-adaptive cultivation, and digital land use monitoring can raise yields, reduce environmental impacts, and strengthen ecological accountability, but their benefits must be made accessible across the entire value chain, including for small producers in developing regions. Inclusive technological adoption is key to ensuring that sustainability transitions do not deepen existing disparities. Equally important, these technologies can help reconfigure global trade flows by improving the production competitiveness of emerging regions, diversifying supply away from over-reliance on a handful of exporters.

In this context, the future of the soybean trade must move toward a paradigm of resilient governance, which is integrated framework that combines policy coordination, technological innovation and diffusion, and market transformation. First, multilateral cooperation is paramount. Major producer countries (e.g., Brazil and the United States) and key importers (e.g., China and the European Union) should work toward harmonized sustainability standards to prevent the spatial shifting of environmental burdens due to regulatory misalignment. Trade agreements must incorporate binding environmental clauses and establish compensation mechanisms that make forest conservation economically viable for producing nations. Second, technological tools must be deployed across the entire value chain. From satellite surveillance to digital traceability, innovations should underpin transparent and equitable trade systems and not merely serve as competitive advantages for dominant actors. Third, market transformation should be catalyzed from the demand side. Mechanisms such as carbon labeling, green procurement policies, and sustainability-linked finance can help generate robust market demand for deforestation-free and climate-aligned soybeans.

A vital yet often overlooked dimension of sustainability involves geographic diversification of soybean production. Solving structural imbalances in the soybean trade, which is currently reliant on a narrow band of exporters, requires unlocking the production potential of underutilized regions such as Northeast Asia, Central Asia, and sub-Saharan Africa. These areas possess significant agroecological potential, and with adequate capital investment, technology transfer, and institutional support, they could emerge as new pillars of global supply. Their development would alleviate ecological stress in overexploited regions and help construct a more resilient and multi-nodal supply network. However, significant challenges remain; insecure land tenure, limited infrastructure, weak agronomic knowledge bases, and fragmented policy regimes continue to impede investment and productivity in these regions. Addressing these constraints requires not only technical assistance but also legal harmonization, cross-border collaboration, and capacity-building initiatives tailored to local socio-political contexts.

Crucially, the future of the soybean trade also hinges on equity challenges. If sustainability policies disproportionately favor large-scale agribusinesses, or if technological barriers exclude smallholders, indigenous peoples, and marginalized actors, then SDGs will remain unattainable. Inclusive participation and benefit sharing must be central to any green transition. Moreover, geopolitical rivalry should not obstruct environmental cooperation. The long-term interests of China, the United States, and the European Union in climate stability and global food security outweigh the short-term disruptions of trade frictions. Ultimately, whether the global soybean trade can achieve a dynamic equilibrium between ecological thresholds and economic demands depends on the collective actions of states, corporations, producers, and consumers. With effective coordination, the soybean sector could evolve into a model of sustainable agriculture. In the absence of cooperation, however, the risks of ecological collapse and food insecurity may be further exacerbated. The decisions made today will shape not only the future of supply chains but also the prospects for sustainable coexistence between humanity and nature.

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Science and Disruptive Technology Program, AIRCAS (grant 2024-AIRCAS-SDPT-15), the National Natural Science Foundation of China (grant 42471372), and the Open Project of the State Key Laboratory of Efficient Utilization of Arable Land in China, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (EUAL-2025-03).

AUTHOR CONTRIBUTIONS

D.P., L. Yu., and B.Z. conceived the study, designed the analytical framework, contributed to writing, and supervised manuscript development. Hongchi Zhang led the writing, literature integration, and figure preparation. Y.Z. supported data compilation, visualization, and early drafting. D.P. contributed substantially to content refinement and section development. L. You, M.C., P.L., J.M.C., and X.Z. provided expertise on trade, crop systems, and environmental impacts. D.A. and P.K. contributed regional insights into Brazil and land use dynamics. J.L. advised on telecoupling and global trade-environment linkages. Q.Z., M.L., H.L., J. Hu., Z.L., Jianxi Huang, Z.S., S.Z., F.W., X.F., H.P., K.S., Z.P., Hankui Zhang, P.H., Jingfeng Huang, X.L., Y.X., and A.H. contributed to thematic input, literature review, and manuscript refinement. All authors reviewed and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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