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Pesticide-related risks embodied in global soybean trade

Highlights

- Trade is potentially benefiting global soybean pesticide risk control
- Trade concentrates risks related to soybean pesticide use in a few countries
- Trade measures hold great potential to mitigate the long-term risks of soybean pesticides
- Reconsider trade's role and foster global collaborations in food-pesticide-trade nexus

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In brief

Wang et al. establish an integrated framework to explore the linkages among global soybean trade, pesticide use, and their associated environmental and health risks across 197 countries. Their findings offer insights into the implications of trade for the sustainable management of soybean pesticides and their associated risks, thus helping cope with the "soybean-pesticide-trade" nexus challenges and safeguard food security.

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Pesticide-related risks embodied in global soybean trade

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SCIENCE FOR SOCIETY The widespread use of pesticides in food production systems impacts human, animal, and ecosystem health. Food trade complicates the issue, as it can separate consumption from production, shifting pesticide-related burdens from consumers to producers across regions. However, there is a lack of clarity on pesticide footprints and their associated impacts embodied in the global food trade, impeding sustainable pesticide management. Our research develops an integrated framework to assess nation-specific environmental and health burdens linked to pesticide use along the global soybean trade. Our study identifies a concentrated pattern of embodied soybean pesticide footprints and their related risks, as well as a declining contribution of trade to overall pesticide-related risks. Our findings reveal the potential of trade in reducing environmental-health risks associated with soybean pesticides and underscore the need to rethink the role of agricultural trade in global pesticide management.

SUMMARY

Pesticides may help safeguard food security but endanger the local ecosystem and farmer health. The globalization of the food trade is masking such impacts by separating production from consumption, and its effects on pesticide use and their related risks remain unclear. Here, we provide a map of the environmental and health risks associated with pesticide footprints along the soybean trade across 197 countries. We find that approximately 64% of soybeans were traded globally, embodying ∼55% of environmental-health risks linked to ∼108 kt of pesticide use. Notably, trade soybean pesticide footprints and their associated environmental-health risks are concentrated in a few hotspot nations, including the USA, Brazil, and Argentina. About 30 kt of future increase in soybean pesticide use and ∼6% of their related environmental-health risks can be offset by reducing 80% of soybean traded from high-pesticide-use-intensity nations to lower ones. Our results highlight the necessity of rethinking the role of agricultural trade in global pesticide management.

INTRODUCTION

Pesticide applications in food production and their associated severe risks to ecosystems and human health have typically been considered a local or regional issue that threatens the Sustainable Development Goals (SDGs) (e.g., zero hunger, good health, and well-being, etc.).[1,2] Many countries have responded by implementing a range of regulations within their territories.[3,4] International food trade is globalizing the issue of pesticide-use-related burdens by geographically separating consumption from

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production, thus shifting these burdens from consumers to producers.[5,6] Similar transboundary stresses induced by food trade have been explored through tracing embodied environmental footprints, including water depletion,[7,8] land use,[9,10] biodiversity loss,[11,12] greenhouse gas emissions,[13,14] etc. These findings demonstrate the substantial embodied cross-border burdens in the global agricultural trade, thereby enhancing the understanding of telecoupling effects[15] and guiding global governance in tackling various food-environment-health nexus challenges. Although some studies have assessed the effects of pesticide residues or pesticide regulations on the global food trade,[16,17] pesticide footprints embodied in the international food trade and their associated impacts are rarely explored, posing challenges for the global management of pesticide-related risks.

Soybean, as the largest source of plant-based protein worldwide, plays a crucial role in the human diet and livestock production, with approximately 65% of the global protein feed provided by soybean meal.[18,19] As soybean production is predominantly centralized in a handful of countries (e.g., the USA, Brazil, etc.), international trade has become increasingly important in meeting the global demand for soybeans.[16] The global trade volume of soybeans has increased more than 5-fold, from 27 million tonnes (Mt) in 1990 to 173 Mt in 2020, exceeding the growth rate of wheat, maize, rice, and total coarse grains (see Figure S1). With soybean production heavily dependent on chemical pesticides, including herbicides, fungicides, insecticides, etc.,[20,21] it is imperative to understand the implications of this "soybean-pesticide-trade" nexus for the sustainable management of soybean pesticides and their associated risks. Moreover, the projected rapid growth in soybean demand, fueled by various factors (e.g., population growth, increases in per-capital income, demand for livestock products, and diet change), mainly in developing countries,[22] suggests a higher reliance on international trade and intensified pesticide use in satisfying this growing global soybean demand. This further underscore the significance of exploring the nexus and the implications of trade for sustainable global management.

In this context, we aim to inform the global sustainable pesticide risk management by exploring the linkages among global soybean trade, pesticide use, and their associated environmental and health risks. Specifically, we seek to assess the extent to which soybean trade affects pesticide use and their related risks; identify the role of trade in shaping the usage of soybean pesticides and their associated risks; explore the key influencing factors contributing to the role; and investigate the potential of soybean trade in guiding soybean pesticide risk management in the long-term future.

To fulfill these objectives, we developed an integrated framework for evaluating the environmental and health burdens linked to pesticide use along the global soybean trade for 197 countries (details see the experimental procedures section). Firstly, we quantify the footprints of 20 kinds of soybean pesticides and their associated risk indicators (i.e., environmental impact quotient [EIQ] and hazard quotient [HQ]) embodied in the global trade of soybeans and their four processed products. Then, we conduct an integrated analysis of the interplay among the trade flows, embodied pesticides, and pesticide-use-related risks of soybeans. On top of this, we simulate the variations of pesticide use and their related risk indicators under different soybean demand (i.e., low, medium, and high) scenarios up to 2050.

Our results show a highly concentrated pattern and declining contributions of soybean trade, indicating trade is benefiting from soybean pesticide threat control globally. Our future projection further shows that ~30 kt of pesticide use and ~6% of their associated environmental-health risks can be reduced under the medium soybean demand scenario in 2050 by avoiding 80% of soybean traded from higher-pesticide-use-intensity nations to lower ones, suggesting the key role of trade in mitigating soybean pesticide-related risks in the long-term future. Hence, the positive impacts of trade should be expanded in global pesticide risk management.

RESULTS

Pesticide use and its related risks embodied in the soybean trade

Our study estimates that global soybean pesticide use in 2015 was ~195,300 tons (t), mostly equivalent to the total pesticide consumption of Argentina,[23] one of the world's agricultural giants. The use of soybean pesticides led to significant environmental risks, estimated at approximately ~3.3×10^9 of EIQ, and health risks, estimated at around ~1.2×10^{13} of HQ. These risks nearly doubled the combined risks posed by 57 kinds of soybean herbicides applied in the USA in 2015.[24] Of this total, ~87,498 t of pesticide use was attributed to soybean production for meeting the local demands of given countries, which corresponded to ~1.5×10^9 of EIQ and ~5.6×10^{12} of HQ. Despite the soybean trade accounting for approximately 64% of global soybean production, the embodied pesticides and their associated environmental and health burdens constituted only around 55% of the total.

The main factor contributing to the difference in proportions, with 64% and 55% respectively, is the variation in pesticide use intensities across different regions (see Figure 1A). Notably, soybean importers tended to apply pesticides at relatively higher pesticide intensities. For instance, two net importers, China (2.8 kg t^{-1}) and North Korea (2.7 kg t^{-1}), applied considerably high pesticide intensities, almost five times the world average and ranking among the top five in the world (see Figures 1A and S3). Conversely, most exporters maintained pesticide use intensities in line with global averages (0.57 kg t^{-1}). The pesticide use intensities of three dominant exporters (i.e., the USA, Brazil, and Argentina) were less than a quarter of that in China due to factors like field size and crop diversity.[25] For example, China's agricultural management practices, driven by factors like geographical conditions, population, and land resources, are dominated by the intensive farming system that aims to improve the output level per unit of arable land, resulting in higher use intensity of agrochemicals.[26] The USA, Brazil, and Argentina, however, are endowed with the world's most productive soybean-growing area due to their temperate or tropical climate,[27] which allows them to achieve target yields with relatively lower pesticide use intensity. Furthermore, we note a large intensity difference between other exporting and importing countries. The difference in pesticide use intensities between the USA and Japan was 1.1 kg t^{-1}, followed by Brazil and Thailand

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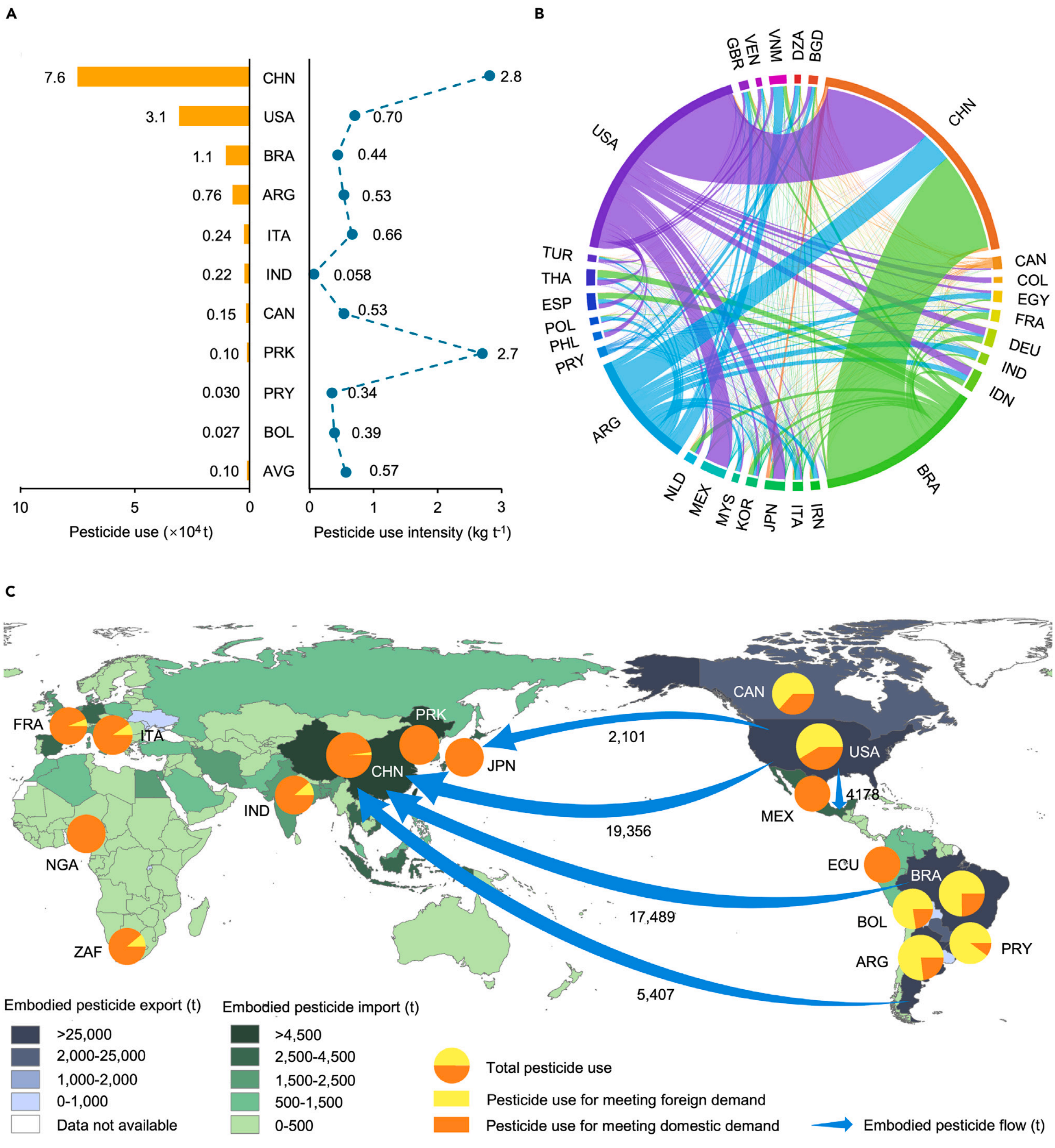
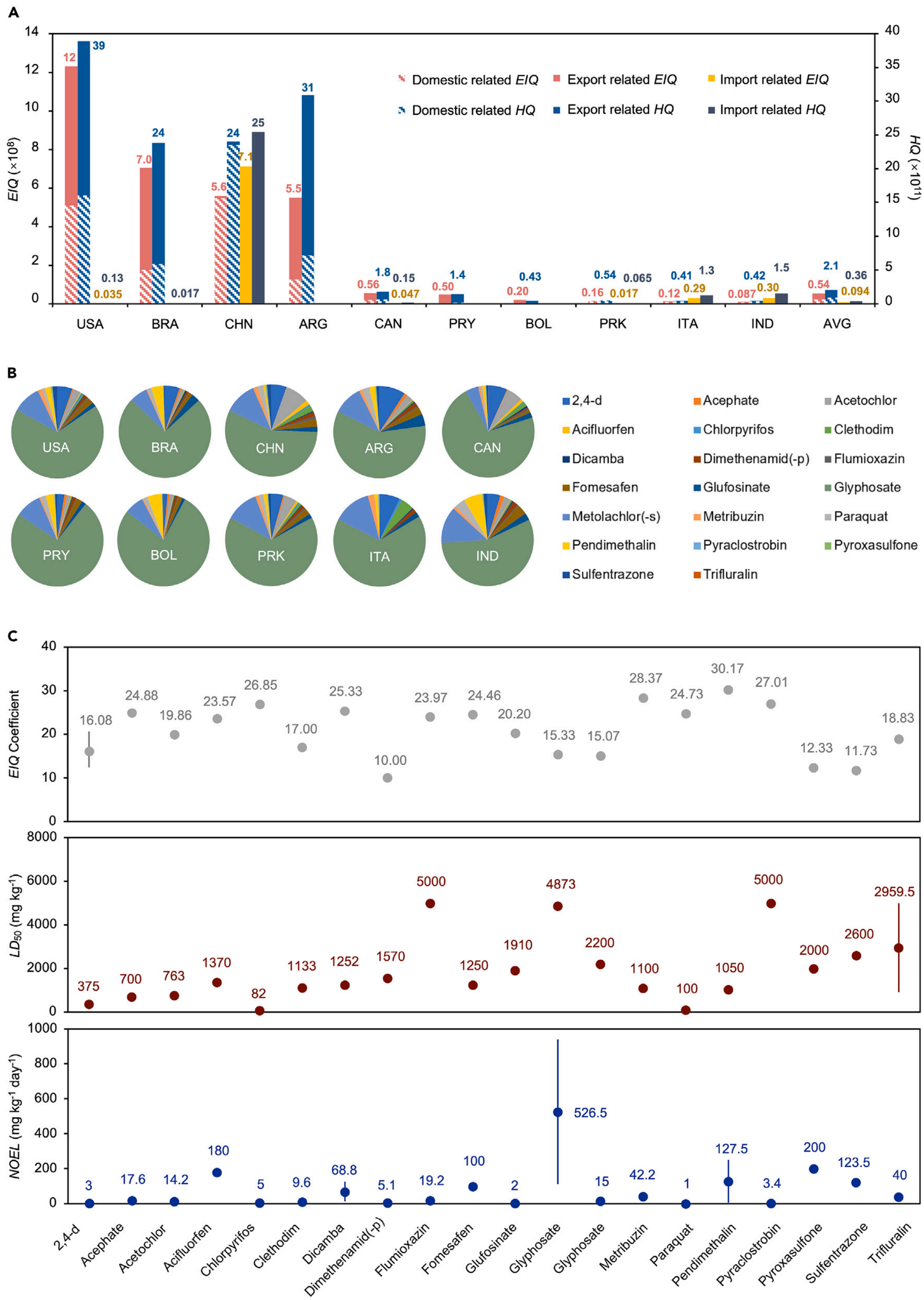


Figure 1. Global pattern of soybean pesticide use

(A) Soybean pesticide use and soybean pesticide use intensity. Detailed data are available in Table S6. (B) Top contributors of embodied soybean pesticide flows. Ribbon colors denote the exporter. To balance complexity and clarity, links with a weight of at least 1% of that of the largest link are exhibited.

(C) Embodied global soybean pesticide footprints. The blue shade represents the net exporters of embodied pesticides. The green shade represents the net importers of embodied pesticides. The size of the pie charts stands for the total amounts of pesticide used. The arrows present the top five pesticide flows embodied in the soybean trade. Detailed data on pesticides embodied in soybean trade for major countries with the most domestic pesticide use are available in Table S2.



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(0.51 kg t^{-1}), Brazil and France (0.24 kg t^{-1}). This indicates a large proportion of soybean products tended to flow from countries with low pesticide use intensities to those with higher ones.

Nation-specific soybean pesticide footprints and associated risks

When mapping the embodied pesticide use and associated risks of soybean trade to each country, we found that a small number of countries bear a significant portion of the global pesticide burden. For the exporting side, nearly 94% (∼100,892 t) of the global embodied pesticide footprints originated from the USA (41%), Brazil (30%), and Argentina (23%) (see Figure S2). Notably, the largest embodied pesticide footprint was from the USA to China (18,936 t), followed by Brazil to China (17,110 t). As expected, these three countries served as the primary hotspots for the environmental and health risks associated with embodied pesticides, which totally accounted for ∼94% of the embodied environmental risks (with ∼1.7×10^9 of EIQ) and ∼95% of the embodied health risks (with ∼6.5×10^{12} of HQ). On the receiving end, China, as the world's largest importer of soybean, contributed ∼40% (∼43,039 t) of the total embodied pesticide imports, of which 45% were from the USA, followed by Brazil (41%), and Argentina (13%). The soybean import-related risks in China accordingly represent a considerable share of the world's total, accounting for ∼40% of environmental risks (with ∼7.1×10^8 of EIQ) and ∼37% of health risks (with 2.5×10^{12} of HQ) (see Figure 2A).

As for national pesticide-related health risks, our results indicate relatively subtle disparities in the pesticide use pattern (see Figures 1 and S2). Notably, although pesticide use in Argentina (∼7,595 t) was lower than that of Brazil (∼10,571 t), the health risks were higher, with ∼3.1×10^{12} of HQ in Argentina and ∼2.4×10^{12} of HQ in Brazil (see Figure 2A). This is mainly due to the heterogeneity in pesticide properties, such as toxicity (dermal, bird, chronic, bee, fish, beneficial arthropod), soil half-life, systemicity, leaching potential, plant surface half-life, surface loss potential, and other physicochemical properties of pesticide active ingredients. For instance, glyphosate, as the most widely used pesticide with a rather low acute and chronic toxicity, accounted for 61% of the total pesticide use on a global scale (see Figure 2C and Table S3). The proportion of glyphosate applied in Argentina (59%) remained at the lowest level among major exporters; by contrast, highly toxic pesticides contributed a large share, particularly 2,4-d (9.1%) and paraquat (2.6%) (see Figure 2B); hence its relatively higher HQ. Brazil, conversely, held the second largest share of glyphosate (74%) among major countries but a relatively lower share of pesticides with high toxicity, leading to its lower health risks (see Figures 2A and 2B).

Potential of trade for future soybean pesticide threat control

Our findings suggest the crucial role of soybean trade in pesticide use and their related risk management. To gain further insight into the potential impact of trade on long-term soybean pesticide risk management, we predict the soybean pesticide use and their related risks under three Food and Agriculture Organization of the United Nations (FAO) future scenarios, namely high (stratified societies scenario [SSS]), medium (business as usual [BAU]), and low (toward sustainability scenario [TSS]) demand for soybeans upon 2050 (see supplemental information). We assume that the management practices related to soybean pesticides (i.e., pesticide use intensity) are in line with 2015 to reflect the role of trade more properly. Figure S4A and Table S9 show the results of soybean pesticide use, HQ, and EIQ under different scenarios in 2050. The global soybean pesticide use is projected to reach ∼481,232 t under BAU (∼499,151 t under SSS; ∼458,416 t under TSS) by 2050, resulting in ∼8.0×10^9 of EIQ and ∼3.2×10^{13} of HQ, more than double of those in 2015. The increasing level of pesticide use varies among countries, ranging from 10^5 t (+1,367%) in Argentina to 0.147 t (+38%) in Mali under BAU. Besides, the USA (90,920 t, +293%) and Brazil (85,206 t, +806%) also show considerable increases in soybean pesticide use. Despite the growth, the embodied pesticide use and their related risks are predicted to fall from ∼107,802 t (∼1.8×10^9 of EIQ; ∼6.8×10^{12} of HQ) in 2015 to ∼92,246 t (∼1.5×10^9 of EIQ; ∼5.6×10^{12} of HQ) in 2050 under BAU, indicating the increased soybean pesticide use in exporters to meet their domestic consumption and the decreased soybean demand of importers.

Further, we conducted simulations to explore the potential of trade in mitigating pesticide threats by adjusting soybean trade flows (see supplemental information). We assume that soybean trade flows from countries with higher pesticide use intensities to those with lower ones are reduced by 20% (general soybean trade policy [T1] scenario), 50% (moderately strict trade policy [T2] scenario), and 80% (extremely strict soybean trade policy [T3] scenario), respectively; the induced soybean demand gaps of importers are filled by increasing the imports from countries with lower pesticide use intensities (see Table S9). The largest reduction of the global soybean pesticide use occurred under T3 of BAU (∼29,747 t, roughly equivalent to the total soybean pesticide use of the USA in 2015), corresponding to ∼5.0×10^8 of EIQ and ∼1.9×10^{12} of HQ reduction (∼6%) (see Figure S4B and Table S9). The global share of pesticide use and their related risks linked to consumption-driven soybean production decreases from ∼18% of T1 to ∼14% of T3 under BAU. This suggests that

Figure 2. Environmental impact quotient (EIQ) and hazard quotient (HQ) of trade-related pesticides and the profiles of soybean pesticides in major countries

(A) EIQ and HQ associated with domestic consumption, exports, and imports of soybean; the units of EIQ and HQ are kg and mg/toxicity, respectively. Detailed information on the results of EIQ and HQ is available in Tables S7 and S8, respectively.

(B) Shares of the twenty soybean pesticides in each major country. Detailed data are available in Table S3.

(C) EIQ coefficient and toxicity of the twenty soybean pesticides. Acute toxicity is expressed as oral rat lethal dose 50 (LD_{50}). Chronic toxicity is expressed as a 24-month oral rat with no observable effect level (NOEL). The higher the values of LD_{50} and NOEL, the lower the pesticide toxicity. The lines represent the error range of the coefficients attributed to various data sources. The lack of error bars for some points is because the error range is too small to be visibly displayed. Detailed information on the toxicity parameters and EIQ coefficient of each soybean pesticide is available in Tables S4 and S5, respectively.

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implementing enhanced trade policies, such as imposing stricter restrictions on trade flows from countries with higher pesticide use intensities to those with lower intensities, would be more effective in reducing both total and trade-related pesticide use.

DISCUSSION

Our results underscore the global nature of the pesticide-use-induced burdens and emphasize the need for global collaborations on pesticide risk management (see Figure 3). In the context of globalization, food consumption in one country may contribute to extensive pesticide use and related environmental-health risks in other countries. If food is imported from countries lacking stringent pesticide regulations (e.g., standards allowing for high pesticide use intensity, poor pesticide composition, dangerous pesticide residue levels, etc.), benefits generated from effective pesticide control policies in one country may be at the expense of the environment and public health elsewhere. Hence, it is necessary to improve globalized pesticide regulations that promote shared responsibilities of pesticide use among different countries, particularly agricultural trade-dependent communities. In the case of Brazil, an agricultural powerhouse worldwide, recent studies have indicated the potential environmental and health ramifications resulting from changes in pesticide regulations in Brazil.[16] These consequences are not limited to Brazil but extend to its trade partners, highlighting the importance of cross-country cooperation in upholding food safety. Besides, recent research has underscored the necessity for enhanced attention to the management of soybean-related resource use against the background of international trade, sectoral responsibility, and the broader implications on the environment and health.[28,29] Our study reinforces these perspectives and proposes an integrated method framework for assessing the environmental and health risks associated with pesticide use in the global soybean trade, contributing to the pressing managerial needs in global pesticide risk.

Also, our findings highlight the key role of food trade in pesticide use and pesticide-use-induced risks. In terms of soybeans, our results show that countries with lower pesticide use intensities tend to export more soybeans than those with higher ones, indicating a potential positive effect of international trade in global soybean pesticide threat control. The scenario analysis serves as an illustration of and a warning about the potential negative consequences induced by the ongoing changes in global trade. Indeed, the trade wars between large countries,[30,31] the COVID-19 pandemic,[32] etc. are fueling an anti-globalization movement with the potential to reshape global trade, including agricultural commodities. Many countries (e.g., Russia, Ukraine, Indonesia, Argentina, etc.)[31,33,34] have sought to limit food exports for concerns over food insecurity, hunger, and malnutrition issues. In these contexts, if a retreat from trade occurred in some food exporters with lower pesticide use intensities, it would aggravate the world's total pesticide use and its related environmental and health risks.

Further, our study can provide new insight to explore the linkage between agricultural trade, pesticides, and associated risks (see Figure 3). Prior efforts[14,35] have mainly focused on exploring the substantial embodied stresses in trade and revealing the adverse impacts of trade in each country. From the global standpoint, international trade can be regarded as a burden "reinforcer" or "mitigator," though little attention has been paid to the role of trade in this context. Typically, industrially manufactured goods are exported more from developing countries with higher emission intensities (e.g., carbon emission intensity) to developed countries with lower emission intensities, leading to an increase in pollutant emissions. Although our results indicate that trade holds the potential to benefit global soybean pesticide threat control by facilitating the export of soybeans from countries with lower pesticide use intensities to those with higher ones, thereby reducing the world's total soybean pesticide usage, the contribution of trade related to other agricultural commodities remains unclear. Recent empirical evidence has highlighted the implications of food trade for human health, demonstrating that a substantial proportion of global dietary risks and diet-related mortality worldwide is attributable to international food trade, and whether the contributions of food trade are positive or negative depends on the types of food traded.[36] Therefore, it is imperative to further explore the role of global trade related to other crops, such as wheat, corn, rice, etc. The integrated framework adopted here can help broadly study such a linkage and thus guide pesticide-related risk management.

Some limitations exist in our study. Firstly, the limitation is mainly due to the lack of publicly available data on the proportion of the 20 kinds of soybean pesticides in other countries except for the USA. From the view of toxicology, however, we note that more than half of these pesticides are highly hazardous pesticides (HHPs),[37] which account for a small fraction of numerous pesticides and can pose severe hazards to the environment and human health. This strongly demonstrates the importance of the studied pesticides. Furthermore, the results of our uncertainty analysis show that in the case of low and high estimates of pesticide use intensity, changes in embodied soybean pesticides, EIQ, and HQ in major countries are all within 20% (see Figures S5 and S6), indicating the quality of data underlying is relatively high. Secondly, our analysis may underestimate pesticide use and its associated environmental and health risks in 2050, as it relies on the assumption that pesticide use intensity has remained constant since 2015 due to data limitations. However, this assumption serves to establish a baseline for comparison in this study and ensures that changes in pesticide use induced by soybean demand and related trade variations are the sole factors considered when assessing the associated risks. Despite the possible uncertainty of the data, our results indicate that the soybean trade has strongly affected soybean pesticide use and its associated environmental and health risks across the globe. We encourage more specific data on pesticides to become available to examine the contribution of agricultural trade more accurately.

Notably, although environmental and health risks associated with pesticides are predominantly attributed to direct pesticide application in soybean production, pesticide-contaminated traded soybeans, particularly for agricultural purposes like seeds, and pesticide residues in soybean products in the consumption phase also carry potential risks. Though these fall

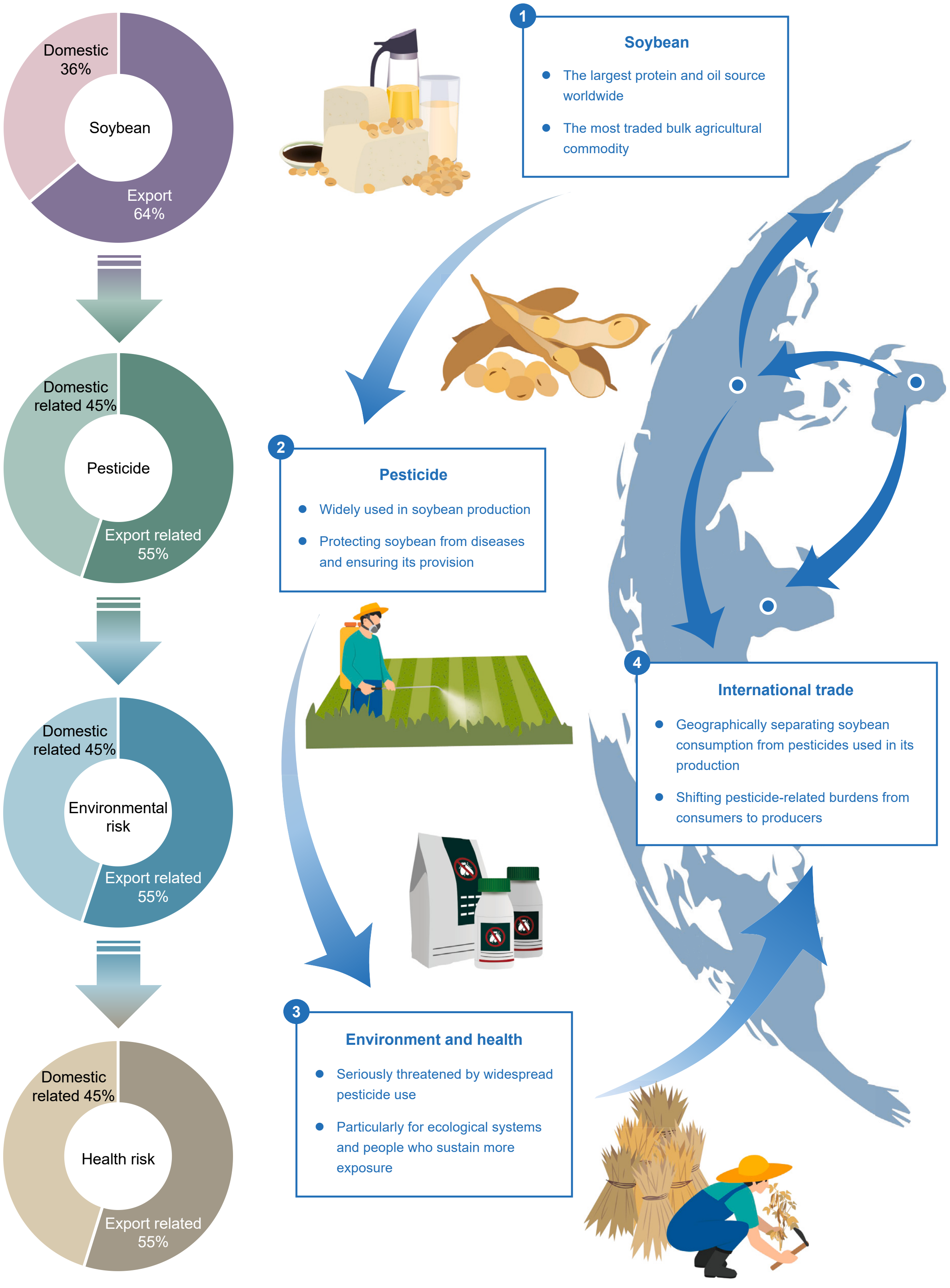

Figure 3. Framework to link the global soybean trade, pesticide use, and environmental and health risks

beyond the scope of this study, this additional dimension holds importance and warrants consideration in future studies. Furthermore, it is imperative to consider the variations in pesticide regulations across different countries, particularly those related to foods, livestock feeds, and environmental media (e.g., freshwater and soil).[38,39] Distinct pesticide environmental quality standards and maximum residue levels in different countries contribute to diverse legal perspectives on domestic, import, or export-related pesticide risks. Empirical evidence has revealed the significant impacts of national pesticide regulations (e.g., pesticide residue standards) on global food trade and the associated health risks.[40–42] This impact is particularly relevant to developing countries that heavily depend on the exports of agricultural commodities, due to their application of less safe pesticide use techniques, the prevalence of poor health conditions among their population, and the use of more toxic pesticides. A broader exploration in this domain would help refine the understanding of the cross-border migration of pesticide-related risks associated with global agricultural trade. These improvements are crucial for formulating more targeted policies concerning global food trade and pesticide risk management in the uncertain future.

Based on our findings, we urge the implementation of more targeted trade policies for soybeans, particularly in the four hotspot nations (i.e., the USA, Brazil, Argentina, and China) due to their highly concentrated pattern. We encourage to take collaborative actions on the soybean trade, such as by closely monitoring trade flows between countries and developing transparent pesticide-labeling systems to incentivize the use of pesticides at lower intensities or with lower toxicities from pesticide exporters, and creating more holistic food strategies that consider the boundary-spinning nature of food systems and integrate a range of policy domains like agrochemicals, ecological environment, public health, etc.[38,39,43,44] These practices may provide innovative directions to mitigate pesticide use and their related risks that can bring positive effects on addressing food security and sustainable agricultural production.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Peng Wang (pwang@iue.ac.cn).

Materials availability

This study did not generate new, unique materials.

Data and code availability

All the source data used in this paper are derived from the cited references or databases (see the subsections of Trade matrices of soybean and soybean processed products, Pesticide use intensity and pesticide use in soybean trade, and Pesticide-use-related environmental and health risks). The data supporting the findings of this study are provided in the supplemental information. Additional information required is available from the lead contact upon reasonable request.

Trade matrices of soybean and soybean processed products

We established detailed and corrected trade matrices to explicitly characterize the trade flows of soybeans and their processed products among different countries. The original trade matrices for soybeans and their four processed products (including soybean oil, soybean cake, soya sauce, and soya paste) were obtained from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT),[45] which cover the production or trade data of 197 countries with available information in 2015 (the latest year for which all the related data are available) (see Table S1—197 countries considered in the study and their soybean production).

As shown in Figure S7, the bilateral trade matrices for the four processed products were first aggregated into one matrix with values in soybean equivalents, as in Equation 1:

$$\boldsymbol{T}_{\mathrm{s}}(a,b) = \sum_i \boldsymbol{T}(a,b,i) \times (1/F(i)) \times \left(F(i) \Big/ \sum_{i' \in \text{branch}} F(i') \right) \quad \text{(Equation 1)}$$

where $\boldsymbol{T}_{\mathrm{s}}(a,b)$ represents the trade matrix from the country a to the country b with values in soybean equivalents; $\boldsymbol{T}(a,b,i)$ is the trade matrix from the country a to b for the processed product i; $F(i)$ and $F(i')$ represent the technical conversion factor for the processed product i and i', respectively, obtained from the FAO commodity trees; i' stands for the by-products from soybean in the same branch, which means processed products produced at the same time, such as soybean oil and soybean cake. To avoid double-counting mistakes, the third term was introduced hereof by applying the method in reference.[7]

Two issues, however, exist with the trade data. One is bilateral asymmetries, which means importers' records do not match the exporters' records in the same transaction. This can be attributed to many factors, including the application of varying trade systems in data compilation (e.g., General versus Special Trade System), the shipping time lags, and transit trade.[46] To address this issue, we adopted the maximum value, aiming to identify the upper bounds of potential risks associated with pesticide use in the global soybean trade under the worst-case scenario, thus informing decision-making for long-term pesticide risk management strategies. Indeed, the adoption of the maximum value has been successfully used to address global trade issues related to highly hazardous chemicals, including pesticides,[47] demonstrating its reliability and accuracy.

Another issue is missing values (i.e., incomplete data value), in which only one party involved in the bilateral trade (either the importer or the exporter) reports the trade data. This can occur due to various factors, including informal or small-scale trade, non-response and non-cooperation, and complex reporting requirements. To address this issue, we opt for the bilateral data method (i.e., adopting the non-missing declaration when only one of the reports is available) due to its simplicity and effectiveness.[48–50] Notably, this approach has been successfully applied by Gaulier and Zignago[50] in establishing an international trade database at the product level, demonstrating the high level of data quality and reliability it delivers.

With globalization, primary products produced in country A are frequently transported to country B for processing and then to country C for ultimate consumption. With that, some detailed trade data reported in the FAOSTAT may represent re-exports from processing countries. To address this issue, we then corrected the soybean equivalent trade matrix by utilizing an origin-tracing algorithm developed by Kastner et al.[51] to improve the data quality (see Figure S7). This correction methodology, linking the consumption patterns to the original country of primary products, allows to re-assign trade flows to their origins, effectively resolving the transit trade issue. The corrected soybean equivalent trade matrix $\boldsymbol{CT}_{\mathrm{s}}(a,b)$ was calculated as follows:

$$\boldsymbol{CT}_{\mathrm{s}}(a,b) = \widehat{\boldsymbol{c}} \times \left((\boldsymbol{I} - \boldsymbol{A})^{-1} \times \widehat{\boldsymbol{p}} \right) \quad \text{(Equation 2)}$$

$$\boldsymbol{A} = \boldsymbol{T}_{\mathrm{s}}(a,b) \times \widehat{\boldsymbol{x}}^{-1} \quad \text{(Equation 3)}$$

where $\boldsymbol{c}$ is the vector of the share of domestic consumption in the sum of domestic production and imports, $\widehat{\boldsymbol{c}}$ is a diagonal matrix containing the elements of $\boldsymbol{c}$; $\boldsymbol{I}$ denotes an identity matrix with the same dimensions as $\boldsymbol{A}$. $\boldsymbol{p}$ is the soybean production vector, $\widehat{\boldsymbol{p}}$ is a diagonal matrix containing the elements of $\boldsymbol{p}$. $\boldsymbol{x}$ represents the vector of the sum of domestic production and imports, $\widehat{\boldsymbol{x}}^{-1}$ is a diagonal matrix containing the reciprocal elements of $\boldsymbol{x}$.

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Pesticide use intensity and pesticide use in soybean trade

The pesticide use intensity, or in other words, the pesticide use per unit soybean, was then calculated (see Figure S7), as follows:

$$I(a) = \sum_{k}\sum_{g \in a}(R(k,g) \times A(g)) / P(a) \quad \text{(Equation 4)}$$

where $I(a)$ is the pesticide use intensity for the country a (in kg $\cdot$ t^{-1}); $P(a)$ is the soybean production for the country a (see Table S1—197 countries considered in the study and their soybean production), obtained from the FAOSTAT;[52] $R(k,g)$ represents the average application rate of pesticides in class k in grid g, which was collected from the Global Pesticide Grids (PEST-CHEMGRIDS).[53] The PEST-CHEMGRIDS is currently the only publicly available database that provides data on global crop-specific and active ingredient-specific pesticide use. It integrates data from the United States Geological Survey (USGS)/Pesticide National Synthesis Project (PNSP) and FAOSTAT and provides 20 types of most used pesticide active ingredients (i.e., 2,4-d, acephate, acetochlor, acifluorfen, chlorpyrifos, clethodim, dicamba, dimethenamid[-p], flumioxazin, fomesafen, glufosinate, glyphosate, metolachlor[-s], metribuzin, paraquat, pendimethalin, pyraclostrobin, pyroxasulfone, sulfentrazone, and trifluralin) applied to six dominant crop (i.e., corn, soybean, wheat, cotton, rice, and alfalfa) and four aggregated crop classes (i.e., vegetables and fruit, orchards and grapes, pasture and hay, and others) and their globally grid-level application rates at a 5-arcminute resolution. The top 20 types of pesticides represent about 90% of the total soybean pesticide mass used in the USA in 2015. Estimation was conducted by extrapolating USA data, and the variations between countries were considered by accounting for national factors such as the pesticide regulations (bans), approval of pesticide resistance genetically modified crops, and national-level data estimated by the FAOSTAT. $A(g)$ stands for soybean harvested area in grid g (in ha). The data was acquired from a gridded analysis dataset, Global Agro-Ecological Zones Version 4 (GAEZ+_2015),[54] with the same resolution as the application rate. The amounts of pesticides for each grid can thus be quantified by multiplying the average application rate by the harvested area. Then, the grids were divided by country, and the gridded results were aggregated at the country level.

Based on the above calculation, the corrected soybean equivalent trade matrix can be eventually converted into a matrix of pesticide use related to soybean trade (see Figure S7), by the following equation:

$$\boldsymbol{T}_{\mathrm{p}}(a,b) = \boldsymbol{CT}_{\mathrm{s}}(a,b) \times I(a) \quad \text{(Equation 5)}$$

where $\boldsymbol{T}_{\mathrm{p}}(a,b)$ represents the matrix of pesticide use associated with soybean trade from country a to country b.

Pesticide-use-related environmental and health risks

As shown in Figure S7, we further estimated the national environmental and health risks related to international soybean trade by quantifying two risk indicators. The indicator of EIQ was adopted to evaluate the environmental impact of soybean pesticides applied in the production. The EIQ, developed by the New York State Integrated Pest Management (NYSIPM) program of Cornell University, is one of the most widely used methods to measure the environmental risks of specific pesticides.[55] A higher EIQ indicates a higher environmental risk faced by a country due to the application of soybean pesticides. In this approach, the EIQ of the nation a was calculated as:

$$EIQ_a = \sum_k COEF(k) \times APR(k,a) \times HA(a) \quad \text{(Equation 6)}$$

where $COEF(k)$ represents the EIQ coefficient of pesticides in class k, collected from the EIQ database of NYSIPM (see Table S5).[56] Based on the toxicological (e.g., dermal, fish, bird, and bee toxicity) and physicochemical (e.g., soil and plant surface half-life) properties of pesticides, it provides users with newly updated EIQ coefficient values of over 500 agrochemicals.[57] $APR(k,a)$ is the application rate of pesticide k in nation a (in kg ha^{-1}). $HA(a)$ is the national soybean harvested area, obtained from the FAOSTAT.[58]

A HQ method was employed to evaluate the relative toxicity of soybean pesticides being used in soybean production, in which the amounts of pesticides stand for an estimate of exposure, and the toxicity of a pesticide active ingredient represents an estimate of hazard. With that, the results of the HQ offer an assessment of risk. A higher HQ value means a relatively higher health risk suffered by soybean pesticide applicators in a country. Indeed, the indicator of HQ has been regularly adopted in many studies,[24,59,60] despite being represented in different ways, to compare the relative toxicity of pesticides, herbicides, and other toxins. Here we referred to Kniss's study[24] and defined the HQ indicator of the nation a as:

$$HQ_a = \sum_{k=1}^{N}(\mathrm{Amount}_k \times HA(a)) / \mathrm{Toxicity}_k \quad \text{(Equation 7)}$$

where N represents the total number of pesticide active ingredients (for this study, $N = 20$ as we cover 20 kinds of soybean pesticides); Amount_k is the gross weight of pesticide active ingredients applied per hectare in class k (in mg ha^{-1}), where the gross weight of pesticide active ingredients was obtained from the pesticide footprint matrix $\boldsymbol{T}_{\mathrm{p}}(a,b)$ and the national soybean harvested area data was from the FAOSTAT;[58] $\mathrm{Toxicity}_k$ is the acute or chronic toxicity value for pesticide active ingredients in class k, obtained from chemical toxicity databases, reports, and literature.[61–64] Acute toxicity is represented by oral rat lethal dose 50 (LD_{50}), whereas chronic toxicity is expressed as a 24-month oral rat no observable effect level (NOEL). According to the U.S. Environmental Protection Agency (EPA)'s hazard classifications and label requirements,[65] pesticides with oral LD_{50} values greater than 5,000 mg kg^{-1} are placed in category IV, which is the least toxic category. From the view of registrants, it is unwarranted to perform a limit test or a point estimate for identifying these values.[24] Hence, 5,000 mg kg^{-1} was uniformly adopted herein as a conservative estimate of the LD_{50} for those pesticides.

Scenario analysis

To inform the policymaking in soybean pesticide risk control, we further assessed the potential impacts of trade on mitigating risks related to soybean pesticide use. We conducted an evaluation of pesticide use and its associated environmental and health risks across various soybean demand scenarios up to 2050. The extent of change observed in simulated pesticide use and risk indicators (i.e., EIQ and HQ) serve as key metrics for assessing the role of soybean trade in soybean pesticide risk control; a greater reduction of these indicators highlights the enhanced potential for soybean trade to contribute to pesticide risk mitigation in the long-term future.

Table 1 shows the description of the baseline and additional future scenarios. We established the baseline scenario (T0) using the results of 2015, including pesticide use and its related environmental and health risks. This scenario mirrors the conditions under the current soybean trade policy and serves as a reference point for benchmarking pesticide use and its associated risks across different soybean demand scenarios in the future. Then, we explored three soybean demand scenarios for 2050: BAU scenario, TSS, and SSS, representing medium, low, and high soybean demands, respectively. Each scenario is derived from alternative scenarios for possible futures designed by the FAO Global Perspective Studies Team.[66]

As shown in Figure S7, we first estimated the national soybean demand under the three future scenarios for 2050. The soybean consumption data for 2050 (including food use, feed use, and other use) of 123 countries or regions was collected, which is provided by the food and agriculture 2050 data portal,[66] as the simulation results of a partial equilibrium model (Food and Agriculture Organization of the United Nations-Global Agriculture Perspectives System [FAO-GAPS]) developed at FAO's Global Perspectives Studies Team. To fill the data gap for the remaining countries, we equally distributed the regional data on soybean consumption in 2050 according to their geographical location and soybean demand proportion in 2015. Then, we calculated the national growth rate of soybean demand in 2050 compared with 2015 and equally allocated it to the soybean equivalent trade matrix of 2015 to forecast the soybean equivalent trade matrix in 2050 (see Figure S7).

Table 1. Description of baseline and additional future scenarios

Scenario	Note	Sub-scenario	Note
Baseline scenario (T0)	reflecting the conditions under the 2015 soybean trade policy	–	–
Business as usual (BAU)	envisioning a future where ongoing challenges in food and agricultural systems persist without resolution, aligning with medium soybean demands	general soybean trade policy (T1)	restricting 20% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		moderately strict trade policy (T2)	restricting 50% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		extremely strict soybean trade policy (T3)	restricting 80% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
Toward sustainability scenario (TSS)	envisioning a future with proactive changes to develop more sustainable food and agricultural systems, aligning with low soybean demands	general soybean trade policy (T1)	restricting 20% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		moderately strict trade policy (T2)	restricting 50% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		extremely strict soybean trade policy (T3)	restricting 80% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
Stratified societies scenario (SSS)	envisioning a less optimistic future with exacerbated inequalities and unsustainable food and agricultural systems, aligning with high soybean demands	general soybean trade policy (T1)	restricting 20% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		moderately strict trade policy (T2)	restricting 50% of soybean trade flows from countries with higher pesticide use intensity to those with lower one
		extremely strict soybean trade policy (T3)	restricting 80% of soybean trade flows from countries with higher pesticide use intensity to those with lower one

Note: detailed descriptions for each scenario are available in the supplemental information.

For each of the three future soybean demand scenarios, we further simulated the trade matrices of various sub-scenarios by adjusting soybean trade flows to different degrees. As shown in Table 1, in these sub-scenarios, the soybean trade flows from countries with higher pesticide use intensities to those with lower ones are assumed to be reduced by 0%, 20%, 50%, and 80%, respectively. To address any resulting gaps in soybean demand for importers, we fill these gaps by importing from countries with lower pesticide use intensity. In cases where a country did not import soybeans from countries with lower pesticide use intensities, we assume that the soybean trade structure of the country remains unchanged.

Based on the soybean trade matrices generated in these sub-scenarios, we then calculate the pesticide use and the indicators of EIQ and HQ following the same method and equations (see Figure S7 and Equations 6 and 7) as the case of 2015. That means, we maintain constant values for pesticide use intensity, soybean harvest area, pesticide types, and properties, focusing solely on the changes in pesticide use and its associated environmental and health risks induced by variations in soybean demand and related trade flows.

Uncertainty analysis

In this study, uncertainties mainly stem from the parameter of pesticide application rate. Trying to give a data range to policymaking in pesticide risk management, we calculated the variance of pesticide use and its related environmental and health risks in the case of low and high estimates of pesticide application rates. The application rates of the studied 20 kinds of soybean pesticides were obtained from the PEST-CHEMGRIDS,[53] which provides an expected range of application rate estimates (denoted by low and high rates) and assumes that random fluctuations in application rates can fall within these ranges. The trade matrix, production, and harvested area of soybeans are kept consistent with previous data. Following the same method outlined in Equations 4, 5, 6, and 7 and Figure S7, we quantify the low and high estimates of soybean pesticide use and their related EIQ and HQ linked to the global soybean trade.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100055.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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