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RESEARCH ARTICLE

How do natural disasters affect agricultural exports?

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Highlights

- Natural disasters significantly reduce agricultural exports from affected countries, with larger negative effects than those in other sectors.
- Different types of disasters affect agricultural exports through distinct cost channels: geological disasters raise transport costs, climatic disasters disrupt production systems, and biological disasters increase storage and compliance costs.
- The adverse effects are stronger in less developed and low-disaster-risk countries, and spill over from primary to processed agricultural products along the supply chain.

Abstract

Global agricultural trade helps to balance the supply and demand for food worldwide, stimulating economic growth and promoting political stability. However, agriculture's inherent vulnerability to extreme weather events and other natural disasters has a significant impact on the industry, which is further amplified through trade and can threaten global food security. This study examines both the mortality and economic losses caused by natural disasters and identifies the mechanisms through which these disasters affect international agricultural trade from 2002 to 2023. The results show that natural disasters cause a decline in the volume of agricultural exports from affected countries, which is much larger than the decline observed in other industries. Despite the high demand inelasticity of agricultural products, which typically leads to increased export prices when production declines, the value of exports still declined significantly over the study period, implying an average annual export loss of 6.21 billion USD and 39,359 jobs. Geological disasters primarily hinder agricultural exports by increasing transportation costs, climate-related disasters by damaging production systems, and biological disasters by increasing storage and compliance costs. We show that disasters have a more devastating effect on agricultural production in less developed countries, which diminishes their global product competitiveness, reduces export prices, and intensifies overall disaster impacts. We also show that countries with low disaster risk, which lack emergency response experience, incur up to 2.053 million USD in agricultural export losses due to disasters. In addition, political risks interact with natural disasters, thereby amplifying their negative impact on agricultural exports. In terms of product heterogeneity, we find that the destructive impact of disasters on primary agricultural products extends through the supply chain to processed agricultural goods, affecting both their production and export. We show that disasters exert an even broader influence on the agricultural system through secondary effects that are 2.83 times greater than the direct impacts. Our findings provide valuable insights and highlight the need for countries affected by disasters to establish disaster prevention and recovery mechanisms to help minimize agricultural trade losses and safeguard global food security.

Keywords: natural disasters, agricultural export, food security, risk assessment, sensitivity analysis

1. Introduction

Since the World Trade Organization (WTO) was established in 1995, global agricultural trade has expanded considerably, increasing in value from 0.88 trillion USD in 1995 to 4.68 trillion USD in 2023, a growth rate of 431.82% (WTO 2023). As a fundamental sector for most countries' economies,

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agricultural trade is pivotal in driving global economic growth, ensuring world food security, boosting farmers' incomes, and maintaining social stability (Clapp 2015; Zhu *et al.* 2021). As of 2018, 81 countries have not achieved food self-sufficiency and 821 million people are underfed, accounting for over 10% of the global population (Gu *et al.* 2021). By leveraging comparative advantages, agricultural trade not only improves resource allocation efficiency in the agricultural sector, but it also diversifies food supplies in terms of both quantity and variety, enhancing global food utilization capacity (Dithmer and Abdulai 2017).

However, the issue of climate change has become increasingly critical to agriculture in recent years, with climate-related natural disasters increasing globally (Noy 2009; Chen and Wang 2022). An annual average of 652 disasters occurred from 2000 to 2023, causing 71,734 deaths and approximately 180.94 billion USD in economic losses (CRED 2023). The United States, China, and India are major producers and traders of agricultural products and are also prone to natural disasters. In many countries, natural disasters destroy significant quantities of crops, which disrupt production of food and animal feed and severely affect the stability of farmers' income (Zhang *et al.* 2017). The impacts of natural disasters extend to other countries through trade, amplifying their effects. Such impacts lead to volatility in global food markets and pose a serious threat to global food security (Oh and Reuveny 2010; Peng and Zhang 2016). For example, China, the world's largest pork consumer, experienced a 21.3% decline in pork production versus the previous year after the outbreak of African swine fever in 2018. Consequently, to sustain domestic supply, China's pork imports surged by 80.72 and 163.43% year-on-year in 2019 and 2020, respectively. In 2023, flooding from heavy rains in India's major tomato-producing regions caused tomato prices to surge from 27 INR kg^{-1} at the start of the year to 178 INR kg^{-1} in July, a sevenfold increase (China Business 2023). Against the backdrop of profound changes in the climate, and in the political and trade relationships, exploring how to prevent and mitigate the impact of natural disasters on global agricultural trade and food security has become a crucial topic.

Research consistently shows that natural disasters affect trade by reducing production, disrupting logistics, affecting consumer demand, and influencing border policies (Martincus *et al.* 2014; Oh 2017; Dallmann 2019). First, these disasters impact production directly and indirectly by reducing the labor supply, thereby affecting trade (Cavallo *et al.* 2013). Second, disasters impede trade flows by damaging infrastructure and increasing transport costs (Feyrer 2021). Martincus and Blyde (2013) note that after the 2010 Chilean earthquake, there was a significant decline in export growth in regions with damaged transport facilities, with more severe road damage exacerbating the decline. Third, post-disaster changes in consumer demand include decreased spending as consumers' incomes fall and their desire to save increases and an increase in trade driven by reconstruction needs for materials (Hsiang and Jina 2014; Meng *et al.* 2015). Fourth, countries often implement post-disaster border measures including export restrictions, tariff reductions, and exemptions (Dadakas and Tatsi 2021; Lee and Zhang 2023). Cheong and Yuan (2017) found a 9.2% increase in Pakistan's exports following EU tariff exemptions after a flood disaster.

Focusing on the agricultural industry, studies highlight the impact of natural disasters on agricultural production (Deng *et al.* 2009). In terms of types of disasters, droughts, floods, and pests notably affect the yield and quality of agricultural products (Godde *et al.* 2021). Concerning crop types, natural disasters severely impact crops reliant on natural resources, such as grains, fruits, and vegetables (Shimada 2022). Developing countries that are often highly dependent on agricultural trade face greater challenges from climate change (Tazeze *et al.* 2012). Regions such as South Asia and Africa that are characterized by large populations, a heavy reliance on agriculture, and limited infrastructure, are particularly susceptible to environmental changes (Aggarwal and Singh 2010). However, due to the unique characteristics of agricultural products, such as uncontrollable production cycles, strict environmental regulations, dependence on transportation, and complex border policies (Dorosh 2001; Kim *et al.* 2023), the impact and mechanisms of natural disasters on agricultural trade differ from other industries and conclusions based on outcomes in other industries may not fully apply to the agricultural sector. There is a dearth of literature that explores the impact and specific mechanisms of natural disasters on agricultural trade.

This study addresses this gap in the literature by systematically exploring the impact and underlying mechanisms of natural disasters on agricultural trade from 2002 to 2023, aiming to provide empirical evidence and a factual groundwork for enhancing the resilience and sustainability of agricultural trade, thereby addressing global food security challenges. First, we conduct a thorough review and summarize the influences of natural disasters on agricultural exports. Second, we apply a structural gravity model to quantify the impacts of natural disasters on agricultural export volumes, prices, and value. Building on this, we analyze the sensitivity of various disaster types to production, storage, transportation, and compliance costs, uncovering the fundamental mechanisms through which these disasters influence agricultural exports. This analysis offers strategies to optimize resource allocation and mitigate disaster impacts on cost management in diverse industries and the government sector. Third, we conduct a comparative analysis of the impact of natural disasters on countries with different levels of development and disaster risk, and on exports of primary and processed agricultural products. We detail the mechanisms through which disasters modulate trade impacts along the supply chain, yielding valuable insights for agricultural producers, exporters, and policymakers on optimizing supply chains and fortifying systemic resilience. Finally, this study examines how natural disasters interact with political risks to jointly impact agricultural exports.

Our study makes the following contributions to the literature. First, we quantify and decompose the effects of natural disasters on agricultural trade in terms of both economic and population losses. This establishes the significant effect natural disasters have on global agricultural

trade and food security, thus contributing to empirical research on natural disasters' economic and trade effects. Second, the study examines the sensitivity of agricultural costs to different natural disasters, uncovering the channels through which these disasters affect agricultural trade. Third, it explores the heterogeneous impacts between natural disasters and agricultural exports, offering a comprehensive perspective to better understand the impact of natural disasters on agricultural exports from multiple dimensions.

2. Data and methods

2.1. Data

In evaluating the impact of disasters, our dependent variable, global agricultural trade data, is derived from the BACI international trade database, managed by the French Centre d'Études Prospectives et d'Informations Internationales (CEPII), for the period 2002 to 2023. We categorize agricultural products using HS 2-digit codes ranging from HS 01 to HS 24. The total number of global agricultural trade observations from 2002 to 2023 is 3,224,529. The primary explanatory variable, disaster data, comes from the EM-DAT database, which encompasses both natural and technological disasters; in this study we focus exclusively on natural disasters. We obtain data on import tariffs, bilateral distance, contiguity, and the presence of trade agreements from the BACI database. After matching the two data sources, we implemented the following procedures: First, due to the lack of data for certain control variables such as tariffs and distance in some countries, we retained only observations, with complete control variable data. Second, given that some countries engage in agricultural trade only sporadically we excluded the 1% of countries with the lowest frequency of agricultural product trade. Third, as the BACI database reports only observations where bilateral trade volume is non-zero, we converted the sample into balanced panel data to accurately estimate the impact of natural disasters on global agricultural trade. After these adjustments, the study encompasses agricultural trade data from 197 exporting countries and 159 importing countries, totaling 1,422,507 samples, accounting for 86.55% of the total global agricultural export.

In the mechanism analysis, the first dependent variable is agricultural production cost. This cost is inversely proportional to output when inputs remain constant. We obtain agricultural production data from the United Nations Food and Agriculture Organization and use the reciprocal of the value of agricultural products to measure production costs. The second dependent variable is agricultural transportation cost, which we measure using the reciprocal of the Logistics Performance–Infrastructure Index published by the World Bank. This Index assesses the quality and availability of a country or region's transportation network, including shipping ports, airports, and railway systems. Scores range from 1 to 5, where higher scores indicate better infrastructure quality. When infrastructure quality is high and transportation networks are efficient, goods can be transported more quickly and safely, with relatively low transportation costs (Riadh 2020). Therefore, we use the reciprocal of the Infrastructure Index to reflect a country or region's transportation costs. The third dependent variable is agricultural compliance cost. After a disaster occurs, some trading partners may impose import restrictions on the affected countries, to reduce agricultural imports from these countries due to quality and safety concerns. When facing such restrictions, exporters in disaster-affected countries are compelled to invest additional resources to ensure their products meet the regulations and standards of the trading partner countries, which increases compliance costs. In this study, we measure compliance costs using the export restriction measures imposed on each country, as recorded in the Global Trade Alert database. The fourth dependent variable is the agricultural storage cost. On the one hand, supply chain disruptions caused by natural disasters usually lead to a sudden increase in consumers' demand for food. On the other hand, consumers may be more inclined to purchase locally-produced agricultural products or certain types of agricultural products. To address this sudden supply crisis, enterprises often need to increase inventory levels to cope with fluctuations in market demand. In this context, the increase in storage costs not only reflects the actual storage expenses but also implies changes in post-disaster market demand and consumer preferences. We measure the storage cost by the quantity of domestic agricultural products in storage at the beginning of a year from the FAO database. Population and GDP data are sourced from the CEPII database.

Descriptive statistics for the variables are shown in Table 1.

2.2. Empirical framework

The gravity model has been used successfully in economics by relating bilateral trade flows to gross domestic product (GDP), distance, and other factors that affect trade (Anderson and van Wincoop 2003). In this study, we follow Peterson *et al*. (2013) and employ a product-level gravity model to estimate the economic impact of natural disasters on global agricultural exports. The theoretical framework of Peterson *et al*. (2013) is built on a general equilibrium model with constant elasticity of the substitution demand system derived by Anderson and van Wincoop (2003). Product-level bilateral trade flows (X_{ijkt}) are explained by the following equations:

$$X_{ijkt}=\frac{Y_{jkt}E_{ikt}}{Y_{kt}}\left(\frac{\tau_{ijkt}}{\Pi_{jkt}P_{ikt}}\right)^{1-\sigma_k} \quad (1)$$

where i, j, k, and t denote the importer, exporter, the HS 2-digit product category, and year, respectively. X_{ijkt} represents the trade value of product k exported from country j to importer i in year t. Y_{jkt} is the value of the total production of product k from exporter j, E_{ikt} is the total expenditure of product k in importing country i. Y_{kt} is the value of the world's output of product k. σ_k denotes the elasticity of substitution for product k. Π_{jkt} and P_{ikt} denote the outward and inward multilateral resistance faced by the exporting and importing countries, respectively. τ_{ijkt} signifies the bilateral trade cost for product k between countries i and j in year t.

Assuming the multiplicative nature of the structural gravity model holds for each period t, we take the natural logarithm

Table 1 Descriptive statistics for variables

Variable	Sample	Mean	Std.	Min	Max
Panel A: Impact evaluation data[1)]					
ln*Value*	1,422,507	4.62	3.12	0	17.12
ln*Q*	1,422,507	3.90	3.14	0	20.41
ln*Price*	1,335,381	1.06	1.43	−9.21	11.98
Disaster	1,422,507	4.03	6.70	0	43
ln*Dist*	1,422,497	8.50	0.97	2.20	9.89
ln*Tariff*	1,422,384	1.40	1.38	0	8.01
Contig	1,422,497	0.06	0.24	0	1
FTA	1,422,497	0.26	0.44	0	1
Panel B: Mechanism analyses data					
ln*Cost.Production*	138,682	0.24	0.33	0.00	0.69
ln*Cost.Transportation*	775	0.32	0.06	0.20	0.59
ln*Cost.Compliance*	3,206	1.31	1.96	0	7.75
ln*Cost.Storage*	2,750	5.30	3.36	0	13.90
ln*GDP*	128,382	18.10	2.43	0	24.05
ln*POP*	130,359	9.39	1.83	2.56	14.18

[1)] The minimum value of ln*Price* is less than 0 because some sample prices are less than one.

of all variables:

$$\ln X_{ijkt}=\beta_0+\beta_1\ln Y_{jkt}+\beta_2\ln E_{ikt}+\beta_3\ln Y_{kt}+\beta_4\ln\Pi_{jkt}+\beta_5\ln P_{ikt}+\beta_6\ln\tau_{ijkt}+u_{ijkt} \quad (2)$$

Natural disasters, as part of the costs of trade, also affect bilateral agricultural trade (Gassebner *et al.* 2010; Meng *et al.* 2015). This paper introduces the exogenous natural disaster variable to study the impact of natural disasters on agricultural exports.

$$\ln X_{ijkt}=\beta_0+\beta_1 Disaster_{jt-1}+\beta_2\ln X_{ijkt-1}+\beta_3\ln(Tariff)_{ijkt}+\beta_4\ln(Dist)_{ij}+\beta_5 Contig_{ij}+\beta_6 FTA_{ijt}+\delta_t+\varepsilon_k+\lambda_i+\vartheta_j+u_{ijkt} \quad (3)$$

The explanatory variable ($\ln X_{ijkt}$) denotes the logarithm of the export volume, price, and value of product k from country j to importer i in period t. The core explanatory variable is the intensity of natural disasters ($Disaster_{jt-1}$). As shown in Table 2, previous studies primarily use three methods to measure disaster intensity: (1) a binary variable indicating the occurrence of natural disasters; (2) absolute variables, including the frequency of natural disasters, the number of people affected, and the economic losses incurred; and (3) relative variables, such as the frequency of natural disasters per unit land area, the proportion of the population affected relative to the total population, and economic losses as a percent of the country's total economy.

However, existing studies on measuring natural disaster intensity face three limitations. First, due to significant differences in the frequency and losses of these disasters across different countries, a binary variable alone fails to capture variations in scale, impact, and loss. Second, countries at different development levels differ in their economic structure, distribution of industries, and economic resilience. Consequently, the impact of natural disasters also differs among countries. As illustrated in Fig. 1, during the sample period covered by this study, natural disasters caused severe economic damage to countries with high levels of economic development, with an average loss of 176.83 billion USD per country, but an average loss of just 26.16 billion USD in less developed countries. However, in those countries natural disasters resulted in significant population losses, with disaster-related deaths averaging 48.72 thousand per country, far exceeding the average of 28.14 thousand deaths in more developed nations. Third, as countries enhance their disaster response capabilities, the number of people affected or killed by disasters of a given intensity generally declines. This study investigates the impact of disasters on agricultural trade globally over the past two decades, noting that measuring disaster intensity solely in terms of economic or population losses can lead to substantial variations. Therefore, we consider both economic and population losses to measure disaster intensity, as shown in eq. (4):

$$Disaster_{jt}=\{\alpha_1(Death_{jt}/POP_{jt})+\alpha_2(Damage_{jt}/GDP_{jt})\}\times 100\% \quad (4)$$

where $Death_{jt}$ is the number of deaths caused by natural disasters in country j in year t; $Damage_{jt}$ denotes the economic damages caused by natural disasters in country j in year t; POP_{jt} and GDP_{jt} indicates the total population and GDP in country j in year t, and α_1 and α_2 represent the proportion of population and economic damages, respectively. We equally weight the two types of damages to measure the intensity of disasters, setting $\alpha_1=\alpha_2=50\%$.

In terms of control variables, we draw on Beckman and Arita (2017) and Oh (2017) and include tariffs implemented by the importing country ($\ln(Tariff)_{ijkt}$), bilateral distance ($\ln(Dist)_{ij}$), contiguity (i.e., a common border) ($Contig_{ij}$), and the existence of a Free Trade Agreement (FTA_{ijt}) to control for other factors that impact trade costs. We also control for the lagged level of agricultural trade between the two countries ($\ln X_{ijkt-1}$). Furthermore, following Permani and Xu (2022) we incorporate importer country fixed effects (λ_i) and exporter country fixed effects (ϑ_j) to control for the characteristics of individual import and export countries, such as economic size and resource endowment, time fixed effects (δ_t) to control for economic conditions in different periods and product fixed effects (ε_k) to control for different product characteristics, such as brand and specifications.

Natural disasters, as exogenous shock events, can affect trade by impacting an entire agricultural supply chain. Disasters directly affect all stages of agricultural activities, including planting, growing, and harvesting, and can therefore

Table 2 Measurement of natural disaster intensity in existing studies

Category	Measurement	Reference
Binary variable	The occurrence of natural disasters	Kim *et al.* (2023); Heinicke *et al.* (2022); Oh (2017)
Absolute variable	Frequency of natural disasters	Permani and Xu (2022); Liu and Li (2022); Raddatz (2007)
	Number of people affected by natural disasters	Shimada (2022)
	Economic losses due to natural disasters	Hemmati *et al.* (2022); Gettelman *et al.* (2018)
Relative variable	Frequency of natural disasters per unit of land area	Skidmore and Toya (2002); Klomp (2016)
	Proportion of the population affected relative to the total population	Keerthiratne and Tol (2017); Noy (2009); Panwar and Sen (2019)
	Economic losses as a percentage of the country's total economy	Sahin (2011); Cavallo *et al.* (2013); Narita *et al.* (2009)

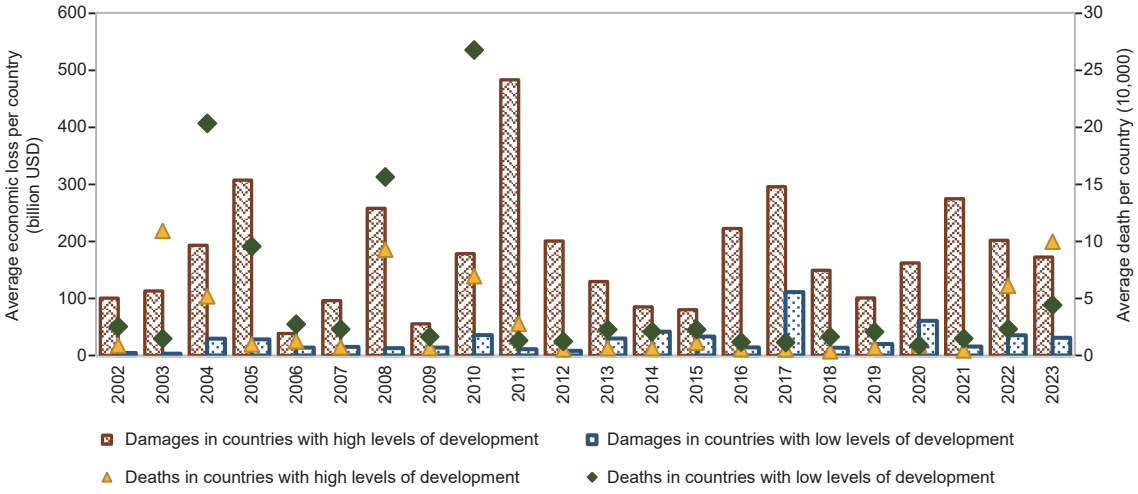


Fig. 1 Economic and population losses in countries at different development levels, 2002–2023. We use the Human Development Index (HDI) from the United Nations Development Programme (UNDP), which reflects a country's economic, social, and educational development. We classify countries into high and low development levels based on their average HDI scores in 2023. Countries with above average scores are defined as high-development countries, while those with scores below the average are defined as low-development countries.

cause a significant decline in agricultural productivity. Weerasekara *et al.* (2022) find that disasters such as droughts and floods can cause rice production efficiency to drop by 2–5%. You *et al.* (2009) find that a 1°C increase in wheat growing season temperature reduces wheat yields by about 3–10%. Inadequacies in warehousing technology can lead to the loss of some of the already-produced agricultural products. Kumar and Kalita (2017) find that cereal grains are the basis of staple food in most of the developing nations, and account for the maximum postharvest losses on a calorific basis among all agricultural commodities. As much as 50–60% of cereal grains can be lost during the storage stage due only to the lack of technical efficiency. The use of scientific storage methods can reduce these losses to as low as 1–2%. Furthermore, as agricultural products are highly perishable it often requires more manpower, material resources, and financial investment to transport them compared to non-perishable products, imposing greater demands on transport methods and storage. Natural disasters can severely damage infrastructure such as roads, bridges, and ports, reducing logistics capacity and further increasing the transportation costs of agricultural trade. Additionally, disasters can affect the quality and safety of agricultural products. To protect domestic food safety, trading partner countries may implement stricter border control policies on agricultural products from disaster-affected countries, increasing compliance costs for exporters (Klomp and Hoogezand 2018).

Considering these distinct mechanisms by which various types of disasters affect agricultural trade and drawing on the existing literature, in this section we categorize natural disasters into geological, climatic, and biological disasters using the EM-DAT database classification. We explore the sensitivity of different costs to different types of disasters from the perspective of the entire industrial chain of production, storage, transport, and trade, as well as their specific mechanisms and pathways using the following model:

$$\ln Cost_{jt}^{y}=\beta_0+\beta_1 Disaster_{jt}^{x}+\beta_2 \ln Control_{jt}+\delta_t+\gamma_j+u_{jt} \quad (5)$$

In this model, $Cost_{jt}^{y}$ represents the cost of agriculture in country j, where y=1, 2, 3, 4 correspond to the costs of agricultural production, storage, transport, and compliance, respectively. $Disaster_{jt}^{x}$ denotes the disaster intensity in country j in year t, consistent with eq. (4); here, x=1, 2, 3 represent geological, climatic, and biological disasters, respectively. $Control_{jt}$ includes control variables such as the population, GDP, agricultural production, and trade costs from the previous period for country j. We include country (γ_j) and time (δ_t) fixed effects to control for the effects of other variables on agricultural costs. β_1 indicates the sensitivity, or elasticity, of agricultural production, storage, transport,

and compliance costs to the intensity of different types of disasters.

2.3. Theory analysis

This paper explores the impact mechanisms of natural disasters on agricultural export markets based on a multi-country, multi-product structural gravity model. We hypothesize that natural disasters primarily affect agricultural export markets in disaster-affected countries by influencing production costs, storage costs, transportation costs, and border compliance costs. In actual trade processes, changes in export market structure are mainly reflected in variations in export volume, export prices, and export value.

$$p_{ij}^k=c_i^k(1+\tau_{ij}^k+\xi_{ij}^k+\psi_{ij}^k) \quad (6)$$

Among these, c_i^k represents the production cost, with a sensitivity to natural disasters denoted by θ_i; τ_{ij}^k represents the transportation cost, with a sensitivity to natural disasters denoted by β_i; ξ_{ij}^k represents the compliance cost, with a sensitivity to natural disasters denoted by λ_i; ψ_{ij}^k is the storage cost, with a sensitivity to natural disasters denoted by ρ_i. θ_i, β_i, λ_i, ρ_i are all greater than zero.

D_i represents the intensity of natural disasters.

$$c_i^k=c_{i0}^k(1+\theta_iD_i) \quad (7)$$

$$\tau_{ij}^k=\tau_{ij0}^k(1+\beta_iD_i) \quad (8)$$

$$\xi_{ij}^k=\xi_{ij0}^k(1+\lambda_iD_i) \quad (9)$$

$$\psi_{ij}^k=\psi_{ij0}^k(1+\rho_iD_i) \quad (10)$$

Combining the relationship between supply and demand, the trade volume of product k between the two countries is obtained as:

$$X_{ij}^k=\left(\frac{c_i^k(1+\tau_{ij}^k+\xi_{ij}^k+\psi_{ij}^k)}{P_j^k}\right)^{-\sigma}\left(\frac{E_j^k}{P_j^k}\right) \quad (11)$$

By substituting the disaster-sensitive elasticities of production costs, storage costs, transportation costs, and compliance costs, the following is obtained:

$$X_{ij}^k=\left(\frac{c_{i0}^k(1+\theta_iD_i)(1+\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)+\psi_{ij0}^k(1+\rho_iD_i))}{P_j^k}\right)^{-\sigma}\left(\frac{E_j^k}{P_j^k}\right) \quad (12)$$

$$p_{ij}^k=c_{i0}^k(1+\theta_iD_i)(1+\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)+\psi_{ij0}^k(1+\rho_iD_i)) \quad (13)$$

For export prices, as natural disasters D_i increase, the production, storage, transportation, and compliance costs of the affected country i will rise, leading to an increase in the price p_{ij}^k of agricultural product k exported to country.

As for export volume, when the export price p_{ij}^k rises, due to the substitution elasticity σ>0, the export volume X_{ij}^k will decrease. If σ is relatively large, meaning demand is highly sensitive to price, the price increase will result in a significant decrease in export volume.

Concerning export value, the export value V_{ij}^k is the product of export volume and export price, which can be expressed as:

$$V_{ij}^k=X_{ij}^k\cdot p_{ij}^k \quad (14)$$

Substituting the expressions for X_{ij}^k and p_{ij}^k yields:

$$V_{ij}^k=\left(\frac{c_{i0}^k(1+\theta_iD_i)(1+\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)+\psi_{ij0}^k(1+\rho_iD_i))}{P_j^k}\right)^{1-\sigma}E_j^k \quad (15)$$

Taking the partial derivative with respect to the natural disaster D_i yields:

$$\frac{\partial V_{ij}^k}{\partial V_i}=E_j^k(1-\sigma)\left(\frac{c_{i0}^k(1+\theta_iD_i)(1+\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)+\psi_{ij0}^k(1+\rho_iD_i))}{P_j^k}\right)^{-\sigma}\frac{\theta_i(\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)+\psi_{ij0}^k(1+\rho_iD_i)+1)+(1+\theta_iD_i)(\beta_i\tau_{ij0}^k+\lambda_i\xi_{ij0}^k+\rho_i\psi_{ij0}^k)}{(1+\theta_iD_i)(\tau_{ij0}^k(1+\beta_iD_i)+\xi_{ij0}^k(1+\lambda_iD_i)++\psi_{ij0}^k(1+\rho_iD_i)+1)} \quad (16)$$

The change in export value depends on the following factors: First, the substitution elasticity σ; if σ>1, demand is extremely sensitive to price, and the price increase caused by natural disasters will significantly affect export volume. Second, the cost sensitivity elasticities θ_i, β_i, λ_i, larger cost sensitivity elasticities would result in a greater impact of natural disasters on cost, thereby significantly driving up prices. The change in export value depends on the price effect and the quantity effect. If the price effect (the increase in trade value due to rising prices) outweighs the quantity effect (the decrease in trade value due to decreasing volume), the trade value may increase; conversely, if the quantity effect is greater, the trade value will decrease.

2.4. Character analysis

Review of global natural disaster characteristics

Although the frequency of natural disasters globally fluctuates year to year, the economic losses they cause show a sharp upward trend. From 1900 to 2023, a total of 16,567 natural disasters occurred worldwide. Since 2000, countries have become more aware of the severe consequences of climate change and the importance of disaster risk prevention and mitigation. Governments have implemented measures with some degree of effectiveness, resulting in a downward trend in the number of disasters, decreasing from 515 in 2000 to 453 in 2023. However, the economic losses caused by disasters continue to rise, from 46.59 billion USD in 2000 to 493.20 billion USD in 2023, representing an increase of approximately 10.96 times. The number of deaths caused by disasters was exceptionally high in some years prior to 2000; for example, the death toll reached 3.21 million individuals in 1920. However, after 2000 the death toll exceeded 100,000, only in 2003, 2004, 2008, and 2010; in other years, the number of deaths remained relatively stable, ranging from 10,000 to 40,000.

Hydrological and meteorological disasters have emerged

as a primary factor impacting global socio-economic development. Between 2000 and 2023, the most frequent economic disasters were floods (3,977 events), storms (2,541), epidemics (868), earthquakes (658), and extreme temperatures (525), accounting for 90.12% of all natural disasters. Floods, which are common in countries with tropical monsoon and rainforest climates such as Brazil, and Vietnam, have caused significant damage. For example, in September 2018, Nigeria experienced severe flooding in the states of Kogi and Niger that affected approximately 2.8 million people, caused over 200 deaths, and resulted in 275 million USD in economic losses. Earthquake-induced property losses were especially notable in certain years. Small earthquakes have limited impact mainly due to human mitigation through specialized construction requirements; however, higher magnitude earthquakes cause substantial damage to housing and infrastructure, affecting supply chains and resulting in costly long-term post-disaster reconstruction. Extreme temperatures and droughts used to be one of the deadliest disasters, but growth in global trade has allowed affected countries to buy food more easily or receive food aid from other regions, significantly reducing drought-related fatalities in recent years. Infectious diseases caused fatalities mainly before 1930, but due to medical advances the annual average death toll from infectious diseases post-2000 has been below 20,000.

Countries with large populations and large land areas are often most affected by natural disasters. The countries that experienced the highest number of natural disasters from 2000 to 2023 are China, the United States, India, Indonesia, and the Philippines, with 635, 591, 400, 377 and 363 natural disasters respectively, accounting for 23.92% of the total (Fig. 2).

The most frequent natural disasters in China are floods, storms, and earthquakes, accounting for 47.37% of the total. A 6.8-magnitude earthquake struck Luding County, Ganzi Prefecture, Sichuan Province on 5 September 2022, killing more than 80 people and causing economic losses of about 2.2 billion CNY. In addition, some parts of China are affected by the monsoon, especially heavy rainfall in the summer, which often leads to a rapid increase in the volume of water in rivers and lakes to form floods, posing a serious threat to agricultural production and property. In the first half of 2023, China's crops were affected by an area of 4,724.7 kha, of which 214.1 kha were out of harvest; and the direct economic losses were 38.23 billion CNY.

The geographic and climatic diversity of the United States, ranging from a humid continental climate in the east to arid and semi-arid climates in the west to tropical climates in the south, results in the country's vulnerability to a wide range of hazards, such as storm, flood, and wildfire. The most serious disaster in the United States is the storm, which accounts for more than 50% of all disasters in years such as 2012 and 2020. Storms can have a severe socio-economic impact by damaging infrastructure, closing office buildings and schools, delaying or canceling flights and trains and, in severe cases, cutting off water and power. In addition, the United States faces significant property damage from the effects of hurricanes. Its geographical location on three sides of the sea facilitates the entry of oceanic water vapor into the land, and the increase in water vapor produces more thunderstorm clouds, which provide the necessary conditions for the formation of hurricanes. Hurricane Sandy in 2012 caused up to 40 billion USD in economic losses in the United States.

India is one of the regions with the most significant monsoon climate in the world. In summer, the southwest monsoon will break out in India from south to north, carrying a large amount of water vapor from the Indian Ocean, which will form clouds and cause rain in India, and bring persistent and widespread heavy rainfall. The Himalayan Mountain range to the north of India intercepts the southwest monsoon in northern India, and under the effect of topographic uplift, rainfall increases further, which can easily lead to flooding. In 2020, cyclones, floods and droughts caused up to 87 billion USD in economic losses in India. In 2005, Mumbai experienced one of the worst disasters in the history of India. Due to unusually intense monsoon rains, Mumbai received more than 944 mm of rainfall in a single day, triggering historic floods that killed about 1,000 people, severely damaged the city's infrastructure and led to a near-total paralysis of public transport, as well as serious public health problems after the floodwaters receded.

Natural disasters and agricultural export In 2023, the top ten agricultural exporters were the United States, Brazil, Germany, China, France, Spain, Canada, Italy, Mexico, and India, collectively accounting for 47.07% of global agricultural exports. Countries prone to natural disasters often play a pivotal role in agricultural trade (Fig. 3). On the one hand, areas with geographical complexities also possess favorable lands and climatic conditions for agriculture. For example, the Philippines, located in Southeast Asia within the Pacific Rim seismic zone, is characterized by an active crust and experiences numerous volcanic eruptions and earthquakes. Despite these challenges, its tropical climate makes it a leading producer and exporter of tropical fruits such as coconuts, bananas, and pineapples, as well as sugar and

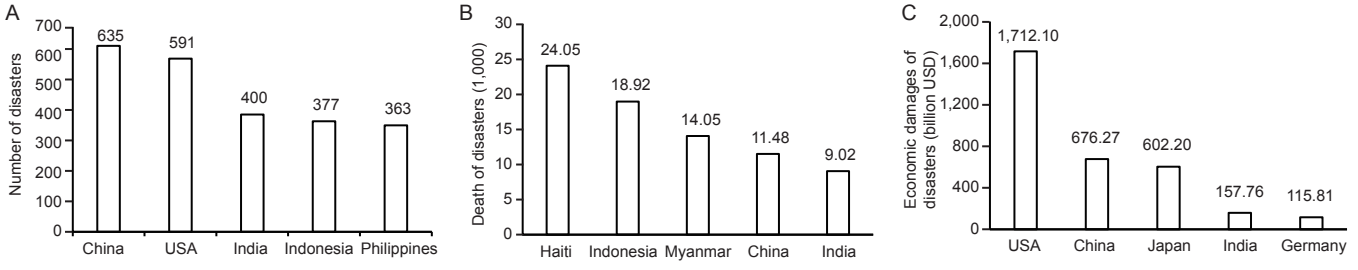


Fig. 2 The top five countries affected by natural disasters, 2000–2023.

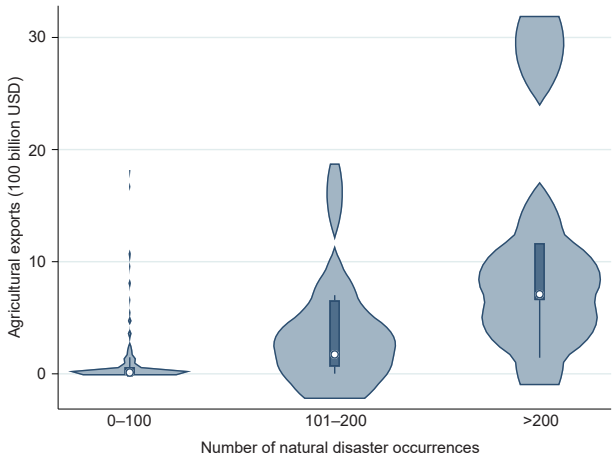


Fig. 3 Natural disaster occurrences and major agriculture exporters, 2000–2023.

coffee. On the other hand, countries with large land masses and large populations are more vulnerable to natural disasters but also have more resources for agricultural production and large consumer markets, and therefore are often the world's major providers to agricultural trade. We selected the United States, Brazil, China, and India for further analysis of their agricultural trade, which are both major global agricultural exporters and highly prone to natural disasters.

In 2023, the United States exported agricultural products worth 174.17 billion USD, representing 12.4% of global agricultural trade. The U.S. exports a diverse range of agricultural commodities, with oilseeds, oleaginous fruits, and miscellaneous grains (HS 12) being the highest-value export category. Other key export products include grains (HS 10), meat and edible meat by-products (HS 02), food industry waste and by-products (HS 23), and edible fruits and nuts (HS 08). The United States' principal export markets are China, Canada, Mexico, Japan, and South Korea, which together account for 61.27% of its agricultural exports.

Brazil, a key player in the agricultural export market, reached 102.3 billion USD in 2023. Brazil's vast agricultural land and favorable climate conditions enable it to produce and export a wide array of agricultural products, further reinforcing its status as a major force in global agricultural trade. The country is renowned for its exports of soybeans, coffee, and sugar, which are among the top global agricultural commodities. Brazil's agricultural exports are primarily directed toward China, the European Union, and the United States. China was Brazil's largest export destination, receiving 35.2% of its total agricultural exports.

China's agricultural exports in 2023 were valued at 98.93 billion USD, representing 7.1% of global agricultural exports. The top five agricultural exports from China include fish, crustaceans, mussels, and other seafood (HS 03), meat, fish, and crustacean products (HS 16), edible vegetables and certain roots and tubers (HS 07), vegetables, fruits, nuts, and other products (HS 20), and other food preparations (HS 21). Major destinations for Chinese agricultural exports include Japan, Hong Kong, the United States, South Korea, and Vietnam, which together account for 43.05% of China's agricultural exports.

In 2023, India's agricultural exports totaled 47.64 billion USD. The country's top five agricultural export categories include animal or vegetable fats and oils, and their cleavage products (HS 15), fish, crustaceans, mollusks, and other aquatic invertebrates (HS 03), residues and waste from the food industries; prepared animal feed (HS 23), preparations of meat, fish, or crustaceans, mollusks, or other aquatic invertebrates (HS 16), and miscellaneous edible preparations (HS 21), collectively accounting for 79.11% of India's total agricultural exports. The primary export destinations for Indian agricultural products are China (20.64%), India (10.55%), the United States (9.87%), Malaysia (4.86%), and Pakistan (4.74%).

Natural disasters impact agricultural exports through various channels (Fig. 4). First, natural disasters can directly affect the growth and harvesting of crops. Approximately 99% of New South Wales, Australia, experienced severe drought in 2018. As a major global wheat exporter, this resulted in a significant decline in crop yields. Consequently, the value of Australian wheat exports decreased from an average of nearly 20 billion AUD annually to approximately 15 billion AUD. Guo and Liu (2020) analyze fluctuations in crop yields from 1961 to 2014 and find that extreme temperatures of 30°C or higher led to a significant decline in cereal crop yields.

Second, natural disasters impact a country's exports by affecting its warehousing capacity. In 2024, flooding in Rio Grande do Sul, Brazil's southernmost state, inundated 80% of the grain stored in warehouses. Consequently, Brazil imported 1 million tons of rice that year, and soybean exports decreased compared to the previous year.

Third, Natural disasters can increase transportation costs, affecting agricultural exports. In 2005, Hurricane Katrina struck New Orleans in the United States, causing a storm surge and levee breaches that flooded 80% of the city. The Mississippi River in New Orleans is a major U.S. shipping port, handling over half of the country's corn and soybean trade annually. Hurricane Katrina damaged the port's infrastructure, shutting down facilities and increasing transportation costs. Consequently, in November 2015, U.S.

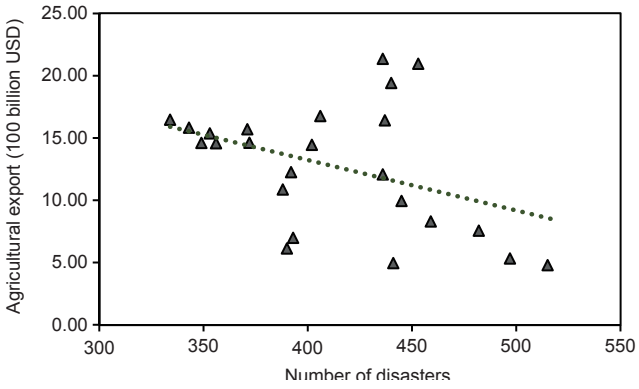


Fig. 4 Natural disasters and agricultural export, 2000–2023.

corn exports declined by 8.14%.

In addition, post-disaster changes in consumer confidence and border policies also affect agricultural exports. The March 2011 earthquake in Japan led to a nuclear accident at the Fukushima power plant, which is in a significant rice and fishing area in Japan. Consumer confidence in Japanese agricultural products eroded after the accident and many countries imposed strict restrictions on food products imported from Japan due to safety concerns. As of the end of 2023, 12 countries and regions had not yet lifted their import bans. A survey of U.S. consumers revealed that one-third reduced their seafood consumption after the Fukushima disaster, and over 50% believed the nuclear incident posed a health threat to Asian seafood. As a result, Japan's agricultural exports fell from 8.2 billion USD in 2011 to 7.98 billion USD in 2012, and 7.14 billion USD in 2013.

The impact of natural disasters on agricultural exports varies across different product types. Following Dong and Cao (2019), we classify agricultural products into primary products (HS01–14) and processed products (HS15–24) to analyze the differential effects of natural disasters on the exports of these two categories. Panel A of Fig. 5 illustrates the differential impact of natural disasters on exporting primary and processed agricultural products. Primary agricultural products are significantly more vulnerable to natural disasters during the export process compared to processed agricultural goods. In the production phase, primary products depend highly on natural conditions; thus, natural disasters directly affect crop yields, livestock health, and overall output. Conversely, processed agricultural products can mitigate disaster impacts through strategies such as raw material stockpiling and process adjustments. For instance, a reduction in wheat production in a disaster-stricken region can be offset by utilizing existing wheat reserves or importing wheat for flour processing, thereby ensuring export stability (Jaffee *et al*. 2010; Mohan 2017). During the transportation phase, the perishable nature of primary agricultural products necessitates either cold storage or rapid turnover. Consequently, damage to infrastructure from natural disasters can easily lead to spoilage or degradation due to logistical delays. Furthermore, bulky or highly perishable food items require additional measures and incur higher costs for storage and transport (Reddy *et al.* 2016). In contrast, processed agricultural products exhibit greater storage stability and are less susceptible to spoilage. For instance, frozen meats and canned goods can be stored for several months, allowing for export resumption following logistical recovery, thereby mitigating large-scale spoilage and losses. Furthermore, primary agricultural products are subject to more stringent inspection and quarantine protocols at border control points. Processed agricultural products, having typically undergone sterilization and pasteurization processes, present lower compliance risks. Consequently, processed agricultural products demonstrate enhanced resilience due to stable raw material supplies, extended storage durations, and reduced compliance risks.

Panel B of Fig. 5 illustrates the impact of natural disasters on the exports of crop products, aquatic products, and livestock products. The export damage to crop and aquatic products is more severe than that of livestock products. This is primarily because crop and aquatic products have shorter production cycles and are more dependent on climatic conditions. Natural disasters, such as droughts, floods, and typhoons, have a more direct impact on their growing environment and harvesting conditions (Breiling 2021). In contrast, livestock production often involves longer rearing cycles, and the livestock industry typically has certain coping and buffering mechanisms, such as feed reserves and shelter protection, thereby reducing the direct impact of natural disasters on exports in the short term. Furthermore, aquatic products are more susceptible to factors such as water pollution and extreme weather conditions. Disasters lead to the deterioration of the aquaculture environment or the shortage of fishery resources, further exacerbating the extent of export damage.

3. Results

The results are presented in two subsections. In the first subsection we discuss the impacts of natural disasters on agricultural exports. The second subsection presents the specific mechanism paths by which different disasters affect agricultural product exports.

3.1. Impact of natural disasters on agricultural exports

Table 3 shows the impact of natural disasters on agricultural exports. Panel A reports results using the full sample, and Panel B presents the results using a winsorized sample.

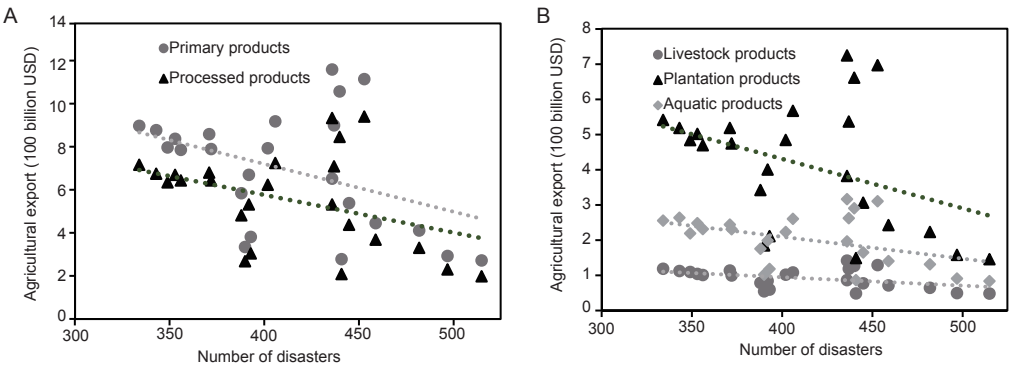


Fig. 5 Natural disasters and different type agricultural exports, 2000–2023.

Column (1) in Panel A shows that the overall impact of natural disasters on agricultural exports is negative. For every 1% increase in the intensity of a disaster, the volume of agricultural exports of the affected country decreases by 0.38%. Although natural disasters cause marked increases in production and transportation costs, which subsequently raise export prices, agricultural products are often deemed essential goods and can exhibit significant demand inelasticity. Disasters such as droughts, floods, and diseases reduce supplies from exporting countries, exerting upward pressure on prices. The results shown in Column (2) indicate that export prices of agricultural products increased by 0.10% after disaster. For example, in July 2012, severe droughts in major food-producing countries, including the United States, the Russian Federation, Ukraine, and Kazakhstan, led to a significant decrease in corn, soybeans, and wheat production. As a result, global food prices rose by 10% compared to the previous month (World Bank 2012).

Despite higher export prices, the negative impact on the value of agricultural exports of the affected countries remains significant. Column (3) indicates that for every 1% increase in disaster intensity, the value of agricultural exports from affected countries decreases by 0.27%. This equates to an average annual export loss of approximately 6.21 billion USD. Considering that agriculture serves as a cornerstone of many national economies, the impact of natural disasters on agriculture has both economic and social implications as it directly affects the livelihoods of millions of farmers. The expansion of agricultural exports not only generates employment opportunities within primary production but also stimulates job creation across the manufacturing, service, trade, and transportation sectors within the supply chain. He (2020) demonstrates that a 1% increase in agricultural exports leads to a 0.302% rise in agricultural employment. Research by Anucha (2019) on Thailand indicates that a 1% growth in the value of Thailand's agricultural exports corresponds to a 0.079% increase in employment. The decline in agricultural exports attributable to natural disasters is estimated to result in the loss of approximately 39,359 jobs globally. Additionally, since agricultural production depends heavily on environmental conditions such as climate, soil quality, and water resources, it is notably seasonal and cyclical. This inherent vulnerability makes agricultural assets and supply chains relatively fragile and more susceptible to the impacts of natural disasters compared to other industries. Gassebner *et al.* (2010) find that natural disasters reduce overall trade by 0.2%. In contrast, our findings reveal that the reduction in agricultural exports is 0.38%, significantly larger than that observed in other industries.

To mitigate the influence of outliers on the estimation results, we conduct a bilateral tail reduction on the variables in the dataset. Specifically, we exclude the highest and lowest 5% of values observed for export value, volume, and price, and re-estimate eq. (3) using the winsorized sample. The results, presented in Columns (4)–(6) in Panel B of Table 3, indicate that natural disasters significantly reduce agricultural exports, confirming the robustness of the baseline conclusion. With respect to the control variables, the regression results show that bilateral distance and tariffs imposed by the importing country negatively affect trade. Conversely, trade in the previous period, contiguity, and the existence of a trade agreement significantly promote agricultural trade between countries which is consistent with the assumptions of the gravity model.

Furthermore, the 2008 financial crisis and the COVID–19 pandemic from 2020 to 2023 have had profound impacts on the global economy and agricultural trade. By the end of 2020, a total of 38 countries and regions had implemented over 1,300 export restriction measures on nearly 200 agricultural products. The contraction in global demand

Table 3 Impact of natural disasters on agricultural exports[1)]

	Panel A: Full sample			Panel B: Winsorized sample		
	Volume	Price	Value	Volume	Price	Value
	(1)	(2)	(3)	(4)	(5)	(6)
$Disaster_{t-1}$	–0.0038***	0.0010***	–0.0027***	–0.0034***	0.0007***	–0.0027***
	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)
$\ln Q_{t-1}$	0.8487***			0.8267***		
	(0.001)			(0.001)		
$\ln Price_{t-1}$		0.6679***			0.6657***	
		(0.001)			(0.001)	
$\ln Value_{t-1}$			0.8445***			0.8203***
			(0.001)			(0.001)
$\ln Dist$	–0.1465***	0.0600***	–0.1422***	–0.1490***	0.0332***	–0.1460***
	(0.002)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
$\ln Tariff_t$	–0.0115***	–0.0063***	–0.0143***	–0.0088***	–0.0009	–0.0133***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$Contig$	0.1455***	–0.0901***	0.1061***	0.1144***	–0.0521***	0.0876***
	(0.007)	(0.004)	(0.006)	(0.007)	(0.003)	(0.007)
FTA_t	0.1100***	–0.0199***	0.1104***	0.1052***	–0.0102***	0.1070***
	(0.004)	(0.002)	(0.004)	(0.004)	(0.002)	(0.004)
Observations	1,059,498	994,515	1,059,498	985,910	873,265	985,942
R-squared	0.830	0.665	0.827	0.785	0.647	0.777

[1)] We include year, product, and country fixed effects in all regressions.
Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

caused by the financial crisis, as well as the trade barriers and logistical constraints triggered by the COVID-19 pandemic, are considered as extreme events that do not represent normal economic conditions. To assess the impact of natural disasters more accurately on agricultural trade and to eliminate the interference of these atypical economic disturbances, this paper excludes data from 2008 and 2020–2023 and conducts the regression analysis again. The regression results after sample adjustment (Table 4) still indicate that natural disasters have a significant inhibitory effect on agricultural exports, thereby reinforcing the robustness of the original conclusions.

Table 4 Robustness analysis: Excluding special years[1)]

	Volume	Price	Value
	(1)	(2)	(3)
$Disaster_{t-1}$	–0.0038***	0.0012***	–0.0028***
	(0.001)	(0.000)	(0.001)
$\ln Q_{t-1}$	0.8428***		
	(0.001)		
$\ln Price_{t-1}$		0.6726***	
		(0.002)	
$\ln Value_{t-1}$			0.8393***
			(0.001)
$\ln Dist$	–0.1447***	0.0605***	–0.1405***
	(0.003)	(0.002)	(0.003)
$\ln Tariff_t$	–0.0103***	–0.0102***	–0.0144***
	(0.002)	(0.001)	(0.002)
$Contig$	0.1422***	–0.0859***	0.1020***
	(0.008)	(0.005)	(0.008)
FTA_t	0.1000***	–0.0153***	0.1022***
	(0.004)	(0.003)	(0.004)
Observations	752,048	705,217	752,048
R-squared	0.820	0.672	0.817

[1)] We include year, product, and country fixed effects in all regressions.
Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

3.2. Mechanism analysis of natural disasters on agricultural exports

Fig. 6 presents the specific mechanism paths by which different types of disasters affect agricultural product exports. Panel A shows the sensitivity of agricultural production cost, storage cost, transportation cost, and compliance cost to different types of disasters, i.e., the cost-disaster elasticity. Panel B depicts how different types of disasters affect agricultural trade through distinct pathways.

Geological disasters, including earthquakes, volcanic activity, and mass movements, primarily hinder agricultural exports by increasing transportation costs. These disasters often damage infrastructure, reducing or even interrupting transportation operations. Such disruptions result in changes of transportation distances and modes, significantly increasing the cost of transporting agricultural products (Feyrer 2021; Friedt 2021). As shown in Line (3) in Panel A of Fig. 6 for a 1% increase in the intensity of geological disasters, the cost of transporting agricultural products in the affected countries rises an average of 0.47%. This finding is consistent with Pelling *et al.* (2002), who demonstrated that the 1995 Kobe earthquake in Japan increased transportation costs by more than 50%. However, due to the relatively limited scope of geological disasters, their impact on agricultural trade is smaller than that of other disaster types. As indicated by Lines (1)–(3) in Fig. 6, Panel B suggests a 1% increase in the intensity of geological disasters in an exporting country decreases agricultural export volume by 0.38%, and export value declines by 0.34%, with no significant change in export

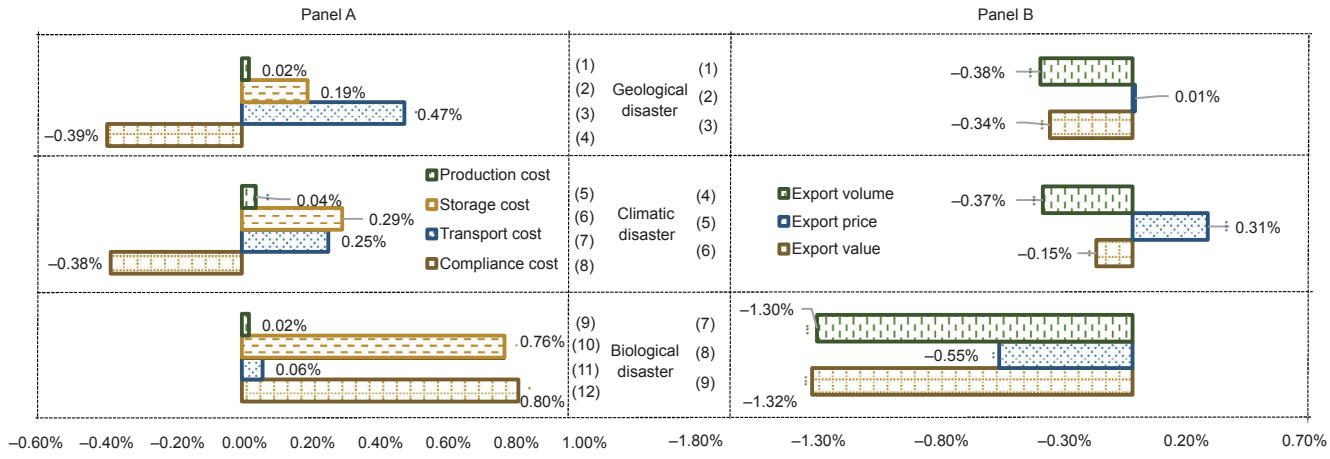


Fig. 6 Mechanism paths of different disaster types affecting agricultural product exports. In Panel A, the horizontal axis shows the regression coefficients for the impact of different types of natural disasters on agricultural production costs, storage costs, transportation costs, and compliance costs. All regressions include year and country fixed effects. In Panel B, the horizontal axis shows the regression coefficients estimating the impacts of different natural disaster types on the volume, price, and value of agricultural exports. The regressions incorporate year, product, and country fixed effects. Natural disasters are categorized as geological, climatic, and biological disasters based on the classification in the EM-DAT database. Geological disasters include earthquakes, volcanic activity, and mass movements; climatic disasters encompass storms, extreme temperatures, fog, floods, landslides, wave action, droughts, glacial lake outbursts, and wildfires; biological disasters cover epidemics, insect infestations, and animal accidents. Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

prices.

Climatic disasters, including droughts, storms, extreme temperatures, and floods, mainly hinder agricultural trade by damaging production systems. These disasters have a wide reach and cause severe destruction, directly damaging agricultural production for a wide range of products from corn to seafood, and indirectly affecting production by damaging raw materials and infrastructure (Qin *et al.* 2020). Additionally, they indirectly impact production by affecting local labor availability (Mohan *et al.* 2018). As shown in Line (5) in Panel A of Fig. 6 of the three types of disasters, agricultural production costs are most sensitive to climatic disasters. When a country experiences a climatic disaster, its agricultural production costs increase significantly, by 0.04%. The damage to agricultural production caused by climatic disasters also has a strong negative impact on agricultural exports. According to Line (4) in Fig. 6, Panel B suggests that for every 1% increase in the intensity of climatic disasters, agricultural export volumes of the affected country decrease by 0.37%. However, since climatic disasters mainly affect primary agricultural products, which have strong demand inelasticity, a short-term decrease in supply leads to a 0.31% increase in prices, partially offsetting the loss in export volume (Line (5), Panel B). Consequently, the export value decreases by 0.15%, which is less than the decrease in export volume (Line (6), Panel B).

Biological disasters, including epidemics, pest infestations, and animal accidents, primarily hinder agricultural trade by increasing storage and compliance costs. As indicated by Line (10) in Panel A of Fig. 6, each 1% increase in the intensity of biological disasters, agricultural storage costs in the affected country increase by 0.76%. Moreover, when an exporting country experiences a biological disaster, its trading partners, concerned about animal health and public health in the disaster-stricken country, may impose trade restrictions, import bans, and strict animal and plant quarantine measures on products from the affected country to protect domestic food safety, thereby significantly increasing compliance costs for agricultural exporters in the affected country. For instance, Line (12) in Panel A of Fig. 6, shows that for every 1% increase in the intensity of biological disasters in an exporting country raise compliance costs for its agricultural exports increase by 0.8%. This finding is consistent with Dadakas and Tatsi (2021) who show that the nuclear power plant accident caused by the 2011 tsunami in Japan led other countries to impose import restrictions on many products from Japan due to concerns about product safety, significantly negatively impacting Japan's exports. Finally, Lines (7) and (9) in Panel B of Fig. 6 indicate that a 1% increase in the intensity of biological disasters is associated with a decrease of 1.30% in average export volume and 1.32% in export value, representing the largest negative impact on agricultural exports.

4. Discussion

4.1. Heterogeneity analysis

Heterogeneous impact of natural disasters on countries at different development levels Countries at different levels of development exhibit significant variations in economic structure, industrial distribution, and economic resilience. More developed countries typically possess more advanced agricultural infrastructure and comprehensive social security systems, greater capacity to maintain supply chain stability, and enhanced access to international cooperation and financial support, enabling them to mitigate the adverse effects of natural disasters more effectively. For example, Hurricane Katrina severely damaged the major port of New Orleans in the United States. However, as demonstrated by Friedt (2021) the U.S. managed to sustain stability in its imports and exports by rerouting trade to adjacent ports. In contrast, less developed countries face more severe consequences from natural disasters. Gassebner *et al.* (2010) find that smaller and less democratic countries experience a more pronounced decline in their import and export flows following natural disasters. To analyze the heterogeneous impacts of natural disasters on countries at different levels of development we use the World Bank's income level classifications to categorize agricultural trading countries into high-development and low-development countries. This framework allows us to examine how natural disasters influence agricultural exports across countries at different levels of development. The regression results are shown in Fig. 7.

In low-development countries, disasters lead to a sharp decrease in agricultural output and export volumes due to their relatively weak disaster response capabilities. Moreover, to ensure domestic food supply security, affected countries may impose temporary export restrictions. For example, the 2010 floods in Pakistan significantly disrupted cotton production, encouraging the Pakistani government to restrict

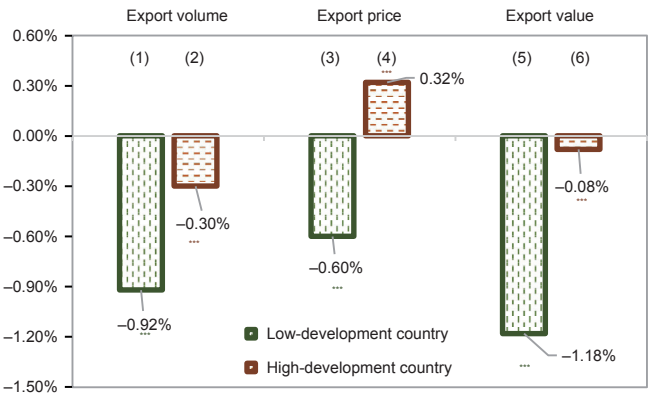


Fig. 7 Impact of natural disasters on agricultural exports across countries at different levels of economic development. The vertical axis represents the regression coefficients for the impact of natural disasters on agricultural exports in countries with different development levels. The World Bank classifies countries into five categories based on income level: High income, Upper middle income, Lower middle income, Low income, and Others. In this analysis, affected countries in the High and Upper Middle-income groups are classified as high-development-level countries; while all others are classified as low-development-level countries. The regression model includes an interaction term between national development level and disaster intensity. Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

cotton to stabilize the domestic market, thereby suppressing overall agricultural exports. Column (1) in Fig. 7 shows that for every 1% increase in disaster intensity, agricultural export volumes in low-development countries decrease significantly, by 0.92%. Since agricultural exports from low-development countries are often heavily concentrated in primary commodities with strong substitutability, these countries face challenges in competing with other exporters when disasters reduce their agricultural production, resulting in price declines (Shimada 2022). Furthermore, the quality of agricultural products is affected to some extent by disasters, which undermines consumer confidence and further reduces export prices. For every 1% increase in disaster intensity, the export price of agricultural products from low-development countries decreases significantly by 0.60% (Column (3), Fig. 7). Column (5) in Fig. 7 shows the combined decrease in export volume and price leads to a 1.18% reduction in agricultural export value for low-development countries. During the study period, annual agricultural export value averaged 49.3 billion USD for low-development countries, the average disaster intensity was 1.18%, and the average annual loss due to disasters was approximately 512.72 million USD.

In high-development countries, the coefficient of the interaction term between the country's development level and the intensity of natural disasters is significantly positive. This suggests that high-development level countries, which possess greater resources, superior infrastructure, and more advanced agricultural technologies and practices (such as irrigation systems, meteorological forecasting, and greenhouse technology), are better equipped to withstand disasters such as droughts, floods, and other extreme weather events. Consequently, their agricultural trade is more resilient and adaptable, experiencing less severe impact from natural disasters. Additionally, highly developed countries have higher food safety standards, making them less vulnerable to import rejection measures. As demonstrated by Sun *et al.* (2021), China's evolving food safety regulations generally restrict trade, reducing imports by 2.24%, on average, for countries with low food safety regulations compared to 0.78% for countries with higher food safety standards. For every 1% increase in disaster intensity, the agricultural export volume of high-development level countries decreases by 0.30% (Column (2), Fig. 7). Moreover, as agricultural products from high-development countries are often more competitive globally and hold significant positions in global trade, these countries enjoy greater pricing power in the global market. When natural disasters increase production costs and reduce supplies, high-development-level countries can adjust prices to adapt to market demand. For example, in the summer of 2012 the world's largest corn producer and exporter, the United States, experienced a 13% reduction in corn supply compared to the previous year due to severe drought, leading to a 32.5% increase in U.S. corn export prices from June to August that year. Column (4) in Fig. 7 shows that a 1% increase in disaster intensity leads to a 0.32% increase in agricultural export prices, partially offsetting the losses faced by high-development countries. Overall, natural disasters cause only a 0.08% decrease in agricultural export value for high-development countries (Column (6), Fig. 7), which is significantly lower than the global average (0.27%) and the decrease in value for low-development countries (1.18%).

Heterogeneous impact of natural disasters on countries with different disaster risk levels Due to geographical and climatic differences, the level of disaster risk and its impacts vary significantly across countries. We categorize global agricultural trading nations into high and low disaster risk countries based on the frequency of disasters they experience. This classification allows us to explore the different impacts of natural disasters on agricultural exports in countries with varying levels of disaster risk. The regression results are presented in Fig. 8.

Fig. 8 shows that for every 1% increase in the intensity of natural disasters, the volume of agricultural products exported from high-disaster-risk countries decreases significantly, by 0.32%, while export prices for their agricultural products increase by 0.07%, resulting in a 0.20% decline in total export value. High-disaster-risk countries tend to bear long-term losses caused by natural disasters and often allocate a certain amount of their expenditures to disaster prevention and emergency response plans. For instance, countries like the United States, Japan, and Chile emphasize the value of earthquake technology in disaster prevention and mitigation and have initiated major research efforts focused on earthquake disaster prevention and mitigation. These measures have been instrumental in promoting agricultural resilience to natural disasters. As highlighted by Wang *et al.* (2024), water-saving irrigation projects in China have been among key initiatives that have contributed to agricultural adaptation. These projects have significantly alleviated the adverse effects of high temperatures on crop yields, accounting for approximately 40% of the country's agricultural climate adaptation effects.

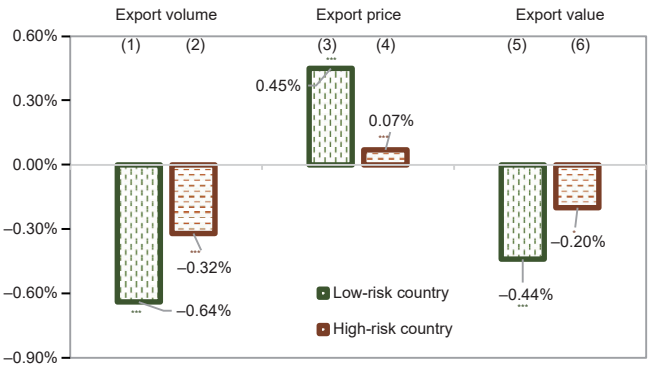


Fig. 8 Impact of natural disasters on agricultural exports across countries with different disaster risk levels. The vertical axis shows the regression coefficients for the impact of natural disasters on agricultural exports in countries with different disaster risk levels. We use the median number of natural disasters occurring in each country from 2002 to 2023 to classify them as high or low disaster risk countries. Countries with disaster occurrences above the overall median are defined as high disaster risk countries, and those below the median are defined as low disaster risk countries. The regression incorporates an interaction term between the country's risk level and the intensity of disasters. Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

In contrast, low-disaster-risk countries, due to their low frequency of disasters, are less prepared than high-disaster-risk countries in protecting infrastructure and resources, and lack experience in establishing robust emergency response and post-disaster recovery mechanisms. When disasters occur in these countries, they may lead to rapid changes in market demand and supply in a short period, and these countries are relatively weak in terms of post-disaster market adaptation abilities, making it difficult for them to adjust export strategies and change market positioning quickly, resulting in a greater impact on agricultural exports. The results in Columns (1), (3), and (5) in Fig. 8 show that for low disaster risk countries, every 1% increase in disaster intensity leads to a significant decrease of 0.64% in export volume, an increase of 0.45% in export prices, and a decrease of 0.44% in export value, resulting in an average annual export loss of 2.053 million USD. This suggests that low-disaster-risk countries, due to their lack of experience in disaster response, suffer greater negative impacts on agricultural exports than high-disaster-risk countries when faced with disasters of the same intensity. Therefore, low-disaster-risk countries should weigh the costs of building an emergency response system against the benefits of reduced agricultural export losses and establish and improve their disaster risk emergency plans.

Heterogeneous impacts of natural disasters on primary and processed agricultural products Do natural disasters have heterogeneous effects and operate through different mechanisms on the exports of various types of agricultural products? Can disasters amplify or mitigate production and trade impacts through industrial chains? Following Dong and Cao (2019), we classify agricultural products into two categories: primary products (HS01–14) and processed products (HS15–24). We then examine the impact of natural disasters on trade in primary versus processed agricultural products, with the regression results presented in Fig. 9.

The results show that disasters adversely affect the farmland and infrastructure, thereby negatively affecting the production and export of primary agricultural products. For every 1% increase in disaster intensity, export volumes of primary agricultural products decrease by 0.29%. Furthermore, natural disasters have a prolonged impact on the already affected agricultural system, exacerbating damage over time. A one-period lagged natural disaster leads to a 0.66% decrease in current export volumes of primary agricultural products. However, the negative impact of disasters diminishes over time; two periods later, the negative impact on primary agricultural product exports falls to 0.03%. This implies that for primary agricultural products, in addition to the immediate impact of a disaster (a 0.29% decline in export volumes), the secondary effects over the next two years cause a 0.69% decline in exports, which is 2.38 times the immediate impact. This pattern is particularly pronounced for climatic disasters, where the cumulative marginal effect on primary agricultural product exports over the three years post-disaster is 1.67%.

For processed agricultural products, the impact of natural disasters on production and export is insignificant because their raw materials can be stored for production. However,

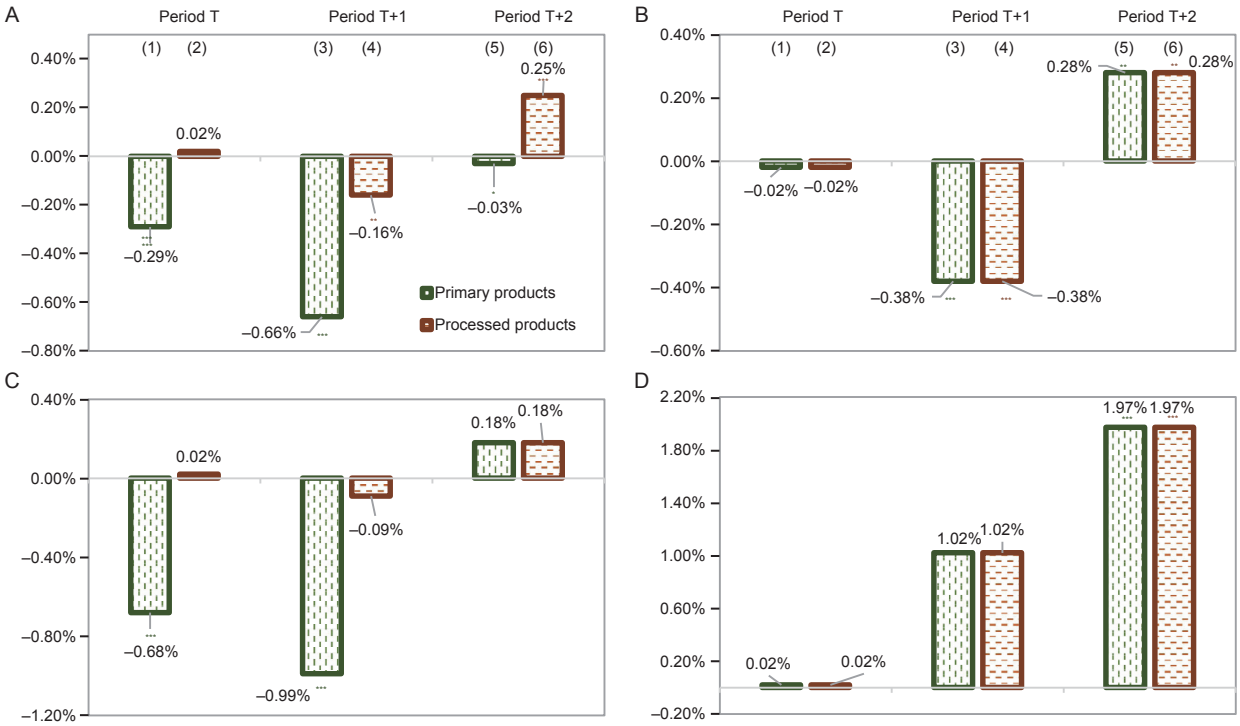


Fig. 9 Impact of natural disasters on primary and processed agricultural exports. A, all disaster. B, geological disaster. C, climatic disaster. D, biological disaster. Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively. The vertical axis in the figure represents the regression coefficients for the impact of natural disasters on primary and processed agricultural exports.

the destructive effect of natural disasters on the output of primary agricultural products is transmitted through the industry chain to processed agricultural products, thereby affecting the production and export of processed agricultural products. As shown in Fig. 9, a one-period lagged natural disaster leads to a 0.16% decrease in the export volume of processed agricultural products. In other words, due to the complexity and fragility of the agricultural product industry chain, the impact of natural disasters is not limited to individual products or regions but permeates throughout the supply chain, exerting influence on the entire economic system.

Heterogeneous effects of natural disasters on plantation, livestock, and aquatic products The impact of different types of natural disasters on the exports of planted products, livestock products, and aquatic products also varies. Based on the WTO's definition of products, this study categorizes agricultural products into three types: plantation products (HS 06–14), aquatic products (HS 03), and livestock products (HS 01, 02, 04, 05). We explore the effects of different types of natural disasters on the export of plantation, livestock, and aquatic products and present the regression results in Fig. 10.

Natural disasters will significantly hinder the export of aquatic and plant products. For every 1% increase in the intensity of natural disasters, the export value of aquatic and planted products will decrease by 0.74 and 0.22%, respectively.

From the perspective of disaster types, geological disasters primarily affect the export of aquatic products. For every 1% increase in the intensity of geological disasters, the exports of aquatic products will significantly decrease by 0.52%. Geological disasters often damage marine ecosystems, reduce fishery resources, or affect fishing areas, thereby decreasing the supply and export of aquatic products. Additionally, aquatic products are highly perishable and require stringent cold chain transportation and storage. Transportation disruptions caused by geological disasters can also lead to significant losses of aquatic products.

Climatic disasters cause the export of aquatic and plant products to decrease by 0.95% and 0.31%, respectively, far exceeding the average impact of natural disasters. The frequent occurrence of climatic disasters alters the production cycles and environmental conditions of aquatic and planted products, increases production costs, reduces supply, and poses threats to the quality and safety of agricultural and fishery products, further suppressing export potential.

Biological disasters have an extremely severe negative impact on the export of livestock products. A 1% increase in the intensity of biological disasters leads to a 1.68% reduction in the export of livestock products. Biological disasters such as epidemics and infectious diseases pose direct threats to the health of livestock, resulting in large-scale deaths or products failing to meet export requirements, severely disrupting normal production and supply chains in the livestock industry. For example, after the African swine fever was introduced to China in 2018, it rapidly broke out with an extremely high mortality rate, causing massive deaths of pigs and a sharp decline in pig inventories and pork production. To control the epidemic, the government implemented culling and embargo measures, further affecting the stability of the pork supply. Due to the difficulty in controlling the epidemic, international concerns about the safety of Chinese pork arose, leading many countries to impose import bans or

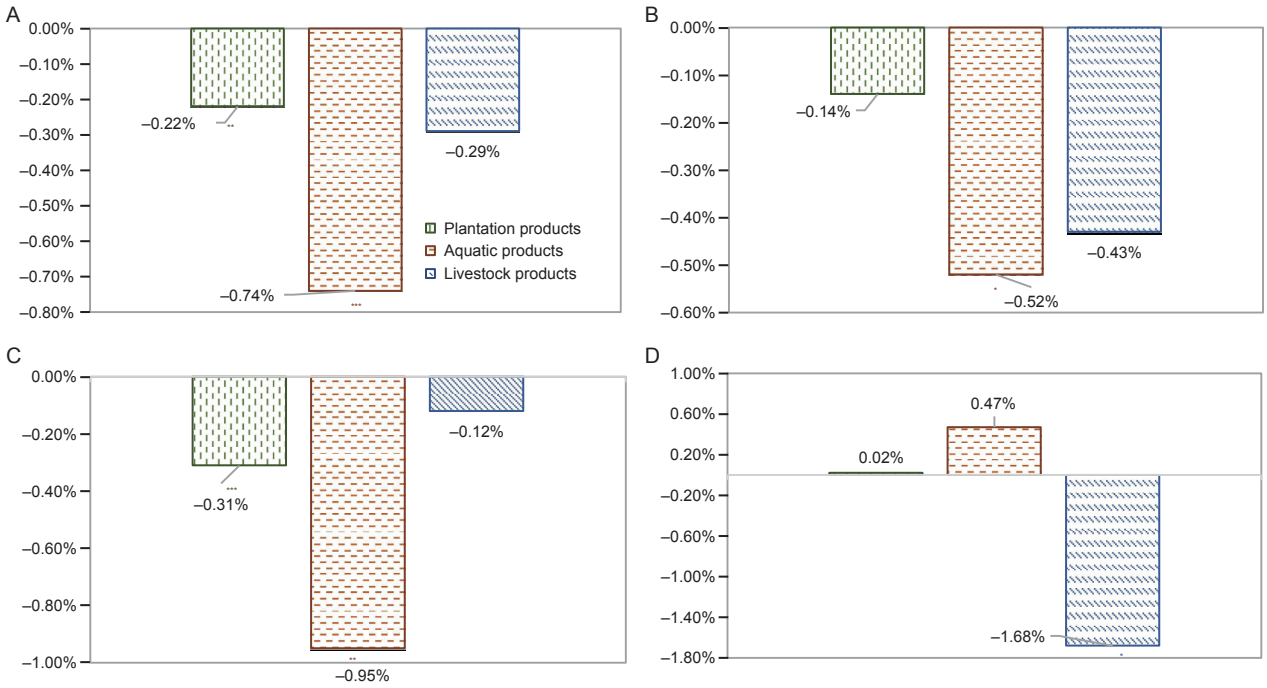


Fig. 10 Impact of natural disasters on plantation, livestock, and aquatic products exports. A, all disaster. B, geological disaster. C, climatic disaster. D, biological disaster. Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

strengthen quarantine measures. As a result, China's pork exports dropped significantly by approximately 30%.

4.2. Interaction impact between natural disasters and political risks

In the globalized economic system, natural disasters and political risks are often interwoven, collectively impacting a nation's export capacity. Political stability and efficient governance enable a country to mobilize resources more effectively to combat natural disasters, implement timely market stabilization policies, and protect industries from severe impacts, mitigating disasters' adverse effects on exports. Conversely, political instability or ineffective governance may lead to inadequate disaster response, exacerbating export losses. This study utilizes the inverse of the World Bank's Worldwide Governance Indicators to measure the political risk level (PR) of disaster-affected countries, and further explores the interaction impact between natural disasters and political risk levels on agricultural exports. Specifically, the study employs reverse indicators of six governance dimensions: Voice and Accountability Risk (VaR), Regulatory Quality Risk (RqR), Rule of Law Risk (RlR), Political Stability and Absence of Violence/Terrorism Risk (PvR), Control of Corruption Risk (CcR), and Government Effectiveness Risk (GeR). These variables range from –2.5 to 2.5, with higher values indicating higher political risk levels.

The regression results are shown in Table 5. Both natural disasters and political risk significantly decrease agricultural exports. Column (1) shows that a one-unit increase in political risk level leads to a 1.29% decrease in agricultural exports. A 1% increase in the intensity of natural disasters results in a 0.29% decrease in agricultural exports. More importantly, political risk also interacts with natural disasters, further amplifying the negative impact of natural disasters. The coefficient of the interaction term between natural disasters and political risks is significantly negative. Oh and Reuveny (2010) discovered that as political risk diminishes, the marginal negative impacts of disasters become less pronounced. In countries characterized by political instability and low governance capabilities, governments encounter more formidable challenges during the post-disaster recovery process. They are incapable of effectively implementing essential market-stabilizing policies or offering adequate support, which significantly decelerates the recovery of agricultural exports.

5. Conclusion and policy recommendation

5.1. Conclusion

Global agricultural export has experienced rapid expansion and plays an increasingly vital role in balancing supply and demand around the world, fostering economic growth, and supporting political stability. However, due to vulnerabilities inherent in the agricultural industry, increasingly frequent natural disasters not only have a severe negative impact on agricultural production in affected countries, but trade amplifies and exacerbates the consequences of these disasters, threatening global food security. Based on an improved structural gravity model, this study is, to the best of our knowledge, the first to examine the impact and mechanisms of natural disasters comprehensively and systematically on international agricultural export against the backdrop of increasingly prominent global climate issues.

Our main conclusions are as follows: First, between 2000 and 2023, the frequency and severity of natural-disaster risks increased significantly, leading to considerable economic losses and human casualties. The primary types of natural disasters during this period were floods, storms, epidemics, earthquakes, and extreme temperatures, with countries such as China, the United States, India, Indonesia, and the Philippines being the most affected. Meanwhile, global agricultural trade demonstrated a fluctuating growth trajectory, with the United States, China, Germany, the Netherlands, and France emerging as major trading countries. It is noteworthy that countries experiencing frequent natural disasters are often also among the leading global producers and exporters of agricultural products. However, natural disasters not only cause direct reductions in agricultural production in the affected countries but also exacerbate the negative impacts on agricultural trade through various mechanisms, including the destruction of infrastructure, the escalation of transportation costs, and the alteration of international trade policies.

Second, a 1% increase in disaster intensity leads to a decline in agricultural product export volumes from affected

Table 5 The interactive effects of natural disasters and political risks on agricultural exports[1)]

	VaR	*RqR*	*RlR*	*PvR*	*CcR*	*GeR*
	(1)	(2)	(3)	(4)	(5)	(6)
$Disaster_{t-1}$	–0.0029***	–0.0024***	–0.0029***	–0.0027***	–0.0027***	–0.0024***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$Disaster_{t-1}$×*PR*	–0.0022***	–0.0032***	–0.0028***	–0.0012*	–0.0023***	–0.0022***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
PR	–0.0129***	–0.0193***	–0.0168***	0.0107***	–0.0129***	–0.0277***
	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.001)
Control variables	YES	YES	YES	YES	YES	YES
Observations	1,052,678	1,052,378	1,052,886	1,052,817	1,052,505	1,052,378
R-squared	0.824	0.824	0.824	0.824	0.824	0.824

[1)] We include year, product, and country fixed effects in all regressions.
Standard errors are in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively.

countries of 0.38%. As agricultural products are usually essential goods with strong demand inelasticity, increases in costs and decreases in supply caused by natural disasters are transferred to product prices. This leads to a 0.10% increase in export prices, which can threaten the stability of global food markets. Although the increase in export prices somewhat mitigates losses caused by a decrease in export volumes, the value of agricultural products exported by affected countries still decreases significantly, by 0.34%, which suggests an average decline in the value of annual agricultural exports of 6.21 billion USD and 39,359 jobs lost. Xu and Kouwoaye (2019) use a structural gravity model to quantify the impact of natural disasters on the scale of service trade imports and exports. They found that exports of services from disaster-affected countries decreased by 0.2 to 0.3%. This suggests that the impact of natural disasters on agricultural exports is significantly greater than in other sectors.

Third, regarding the mechanisms that lead to these results, production costs are most sensitive to climatic disasters, with an elasticity of 0.04% to the intensity of climatic disasters. Regarding transportation costs, for a 1% increase in the intensity of geological disasters, logistics and transportation costs associated with agricultural products in affected countries rise by 0.47%. Compliance and storage costs are extremely sensitive to biological disasters, with the elasticity of 0.8 and 0.76%, but are not sensitive to geological and climatic disasters; in other words, those two types of disasters do not hinder agricultural trade by increasing compliance and storage costs.

Finally, less developed and low disaster risk countries have greater export losses than other countries. Political risks interact with natural disasters, thereby amplifying the negative impact of natural disasters on agricultural exports. Regarding product heterogeneity, aquatic products are mainly affected by climatic and geological disasters; planted products are influenced by climatic disasters; and livestock products are impacted by biological disasters. The adverse effects of natural disasters on primary agricultural products are transmitted through the supply chain to processed products, affecting their production and exports. While natural disasters initially damage the production and trade of primary agricultural products, they do not significantly impact processed products. However, the lagged impact reveals that disasters eventually lead to a decrease in processed agricultural exports. Additionally, the secondary impact of disasters over three years is more than 2.83 times greater than the immediate impact.

5.2. Policy recommendation

Based on the above conclusions, we propose three policy recommendations: First, governments should analyze the risks and costs of natural disasters against the cost of establishing emergency response systems, to formulate the optimal investment in emergency preparedness. Due to their geographical differences, countries around the world face varying degrees and types of disaster risks and should develop disaster prevention, information gathering, and mitigation measures suitable for their specific conditions. When a geological disaster occurs, affected countries should focus on recovering production, logistics, and transportation systems; for climatic disasters, recovering production capacity should be the top priority, and for biological disasters, countries should focus on the quality and safety of their products and the import policies of trading partner countries. For example, after Hurricane Katrina, the United States emphasized improving hurricane prediction and assessment, and its National Hurricane Center has since established a prediction database to better forecast the occurrence, severity, and path of hurricanes. Japan, a country prone to earthquakes, has been developing its “Earthquake Damage Assumption System and Early Earthquake Damage Evaluation System” since April 1996 and formulated emergency plans such as national earthquake insurance.

Second, countries should improve their agricultural disaster prevention and post-disaster governance systems to minimize losses for all parties. Governments should establish an effective agricultural meteorological monitoring system, and employ advanced agricultural technologies to monitor weather and climate conditions in real-time, develop and implement disaster risk assessments, and encourage timely planting structures based on geographical features and disaster risks, thus promoting sustainable agricultural practices. In addition, countries should establish innovative agricultural disaster insurance risk diversification mechanisms. Due to the high-risk nature of the agricultural industry, agricultural insurance underwriters face the risk of excessive payouts in the event of a natural disaster, which negatively impacts the effectiveness of agricultural insurance as a risk management tool; thus, there is an urgent need to establish diverse risk diversification mechanisms. Lastly, governments and the agricultural industry should establish a comprehensive disaster relief and post-disaster recovery planning system that covers aspects such as land restoration, agricultural infrastructure repair, and rural community reconstruction.

Third, agriculture industries in each country should optimize supply chain management to increase flexibility and efficiency and support stable operations in agricultural production, processing, and trade. Initially, the focus should be on enhancing the disaster resilience of primary agricultural products by increasing investment in agricultural technology and disaster-resistant crop varieties. Agricultural producers should be encouraged and educated about how to adopt more disaster-resistant crops and production methods, thereby improving disaster resilience for their primary agricultural products, and reducing the impact of disasters upstream in the industry chain. Additionally, processing enterprises should be encouraged to implement diversified supply chain strategies, including selecting multiple suppliers, and using multilocation production and multichannel logistics. This approach slows risk transmission, reduces dependence on a single link in the supply chain, and helps businesses to better adapt to the uncertainties disasters create. Furthermore, inventory management systems should be optimized to permit real-time inventory management based on updated demand and supply information to minimize

inventory shortages or excesses caused by disasters. At the same time, producers should adopt an emergency stockpiling strategy before the onset of the climatic disaster season to stockpile necessary raw materials and products in advance to mitigate supply chain instability during the disaster period.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, we used ChatGPT 4.0 in order to polish and revise the language expression. After using this tool, we reviewed and edited the content as needed and take full responsibility for the content of the published article.

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