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US-China trade friction and agricultural nitrogen loss in China

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ABSTRACT

Agricultural production, trade and environmental quality are interdependent. The US and China have been the world largest trade partners. However, trade tensions and interest in protectionist policies intensified in recent years. We use a price endogenous partial equilibrium model to systematically examine the impact of increased Chinese tariff on agricultural imports from the US on nitrogen (N) loss in China. The results show that a 25% tariff on US soybean imports increases the acreage of major crops in China by 1.37%. Although aggregate crop acreage increases, the impact on cumulative nitrogen fertilizer uses and the corresponding N loss from cropland is not significant as less N-intensive soybean acreage replaces some of the more N-intensive crops like wheat. However, our estimates show significant heterogeneity in N loss across Chinese provinces, ranging from 0.05% to 2.97% increase. These results identify provinces where remediation measures may be needed to effectively manage the potential increase in nitrogen loss associated with greater soybean production.

1. Introduction

International trade has been a major catalyst for economic growth in the US and China, the world's largest economies, with annual bilateral trade exceeding $500 billion since 2013 (UN, 2020; Krishna et al., 2023). However, there are significant concerns about the impact of international trade on environmental quality (Jayadevappa and Chhatre, 2000; Le et al., 2016; Hu et al., 2021). These concerns are especially pertinent for developing countries like China, where economic growth has been prioritized, often at the expense of environmental quality (Sun et al., 2021; Yu et al., 2023; Chai et al., 2023). Yet, there is a shortage of studies exploring the effects of international trade on environmental quality in developing economies.

The merits of trade liberalization and the role of comparative advantage in economic growth have been well documented (Copeland, 1989; Matsuyama, 1992; Grossman and Helpman, 1993). Previous literature demonstrates the negative effects of trade barriers on economic growth and social welfare (Lawrence, 2018; Qiu and Wei, 2019; Li et al., 2018; Guo et al., 2021). Itakura (2019) estimates that the real GDP of the US and China drop by 0.4% and 1.1%, respectively, if trade barriers implemented in 2018 were to persist through 2035. Nevertheless, protectionist and anti-globalization sentiments have grown significantly recently (Raess et al., 2018; Rodrik, 2018; Dür et al., 2020). While the protectionist trade policies are often motivated by geopolitical, domestic industry, labor support objectives, the discussion of environmental impacts are often absent from the discourse.

The relationship between trade and the environment is complex (Grossman and Kruger, 1995). Prior studies conclude that trade barriers result in inefficient use of scarce resources and unnecessary pollution (Bajona and Kelly, 2012). For instance, the US-China agricultural trade conflict is harmful to the environment due to increased food transportation mileage (He et al., 2019). However, other studies argue that trade frictions may have positive environmental effects. Lin et al. (2019) shows that a 25% tariff would significantly reduce global economic activity, carbon emissions, and PM2.5 related mortality. Similarly, Du et al. (2020) find that the US-China trade war reduces GDP and emissions. Lu et al. (2020) also find that US-China trade war is likely to reduce CO_2 emissions in some regions. However, global CO_2 emissions increase as comparative advantages are not exploited.

Much of the prior literature on trade and environment examines the impacts of trade disruptions on greenhouse gas emissions, while agricultural nutrient runoff studies are relatively scarce. Shi et al. (2016) find that food trade has greatly reduced nitrogen pollution in China. Yao et al. (2021) shows an increase in U.S. nitrogen pollution as farmers shift production from soybeans to more nutrient intensive crops in response to China's tariffs on US soybean. They also find that China would

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experience limited environmental improvement due to the insignificant changes in crop portfolio and harvested area.

Significant environmental impacts of agricultural production intensification in China have been thoroughly documented (Liu et al., 2020; Ma et al., 2022; Wang et al., 2023). China is the third biggest fertilizer user, consuming one-third of the world's total (FAO, 2023). The intensive use of chemical fertilizers involves significant nitrogen losses, resulting in soil, water, and air pollution (Hartmann et al., 2015; Zhang et al., 2015; Ladha et al., 2016; Shortle et al., 2021), and biodiversity loss (Oenema et al., 2009; Zhang et al., 2016).

The nexus between agricultural trade and regional nitrogen (N) loss from crop production in China has been relatively underexplored in academic literature. In this study, we examine the relationship between agricultural commodity trade and nitrogen loss in China using a price endogenous partial equilibrium model with spatial land use and crop production. In particular, we quantify the changes in China's regional nitrogen losses changes in response a tariff on soybean imported from the US.

We examine how a tariff on soybeans imported from the US affects regional fertilizer loss in China as production activities adjust to new trade structures and prices. Our setting resembles the context of the 2018 trade conflict between the US and China. However, our focus is on the environmental impact of a long run structural change in the US-China agricultural trade setting, rather than on the short run effect of a temporary trade shock. The recent US-China trade conflict serves as a motivation rather than an object of evaluation, as protectionist sentiments have been gaining ground among policy makers. As such, it is important to examine the long run potential environmental impacts of a structural change in international trade.

We contribute to prior literature by examining regional impacts on nitrogen loss in China. As our focus is much narrower than Shi et al. (2016) and Yao et al. (2021), we use a multi-region multi-product price endogenous partial equilibrium model that incorporates US-China-ROW (rest of the world) agricultural trade and the Chinese regional agricultural land use and production. The price endogenous partial equilibrium formulation that includes explicit land use is suitable for evaluating agricultural production and associated environmental impacts. Examination of spillover effects to other sectors is outside the scope of our study. We consider several tariff scenarios to estimate the effects on major crop acreages, yields, fertilizer uses and nitrogen losses in 31 Chinese provinces.

The rest of this paper is organized as follows. Section 2 provides a theoretical framework motivating the empirical analysis. Section 3 describes the empirical methodology and data. Results are presented in section 4 and conclusions are in section 5.

2. Theoretical analysis

To provide a theoretical motivation for the empirical analysis, we analytically illustrate the effect of a trade tariff on domestic production and fertilizer use using a parsimonious set up with two agricultural commodity groups. We assume that a trade tariff is imposed on the major imported commodity (soybean) while other agricultural products are unaffected.[1] The objective function maximizes the consumer and producer surplus subject to consumption, production and import balance.

$$\underset{x_i,d_i,e_i,n}{Max\,\pi} = \sum_{i=1}^{2}\int P_i(d) - C(x_1, x_2, n) - p_1(1+\tau)e_1 - p_2 e_2 \quad (1)$$

$$s.t.\, x_i + e_i - d_i \geq 0 \quad (2)$$

where π is the consumer and producer benefits. $P_i(d)$ is the inverse domestic demand function for commodity i = 1, 2. d_i is corresponding domestic consumption quantities of commodity i. x_i is domestic production of commodity i. n is nutrient use. $C(x_1, x_2, n)$ is the cost function for domestic production, with the usual properties: $C_x > 0, C_n < 0, C_{xx} > 0$, $C_{nn} > 0$, $C_{xn} = C_{nx} < 0$, and $C_{x_1x_2} = C_{x_2x_1} \lesseqgtr 0$ depending on the substitute or complementary relationship of x_1 and x_2. The cost function is decreasing in n because fertilizer use decreases the costs of production in the economically relevant quantity range. e_i denotes the imports of product i. p_1 and p_2 are the corresponding international prices. τ is the tariff imposed on imported agricultural product e_1.

From Eqs. (1) and (2), we obtain the effect of the tariff on production as follows:

$$\frac{\partial x1}{\partial \tau} = \frac{C_{nn}C_{x_2x_2} - C_{x_2n}^{2}}{-C_{x_1n}^{2}C_{x_2x_2} + 2C_{x_1x_2}C_{x_1n}C_{x_2n} - C_{x_1x_2}^{2}C_{nn} - C_{x_1x_1}\left(C_{x_2n}^{2} - C_{x_2x_2}C_{nn}\right)} \quad (3)$$

$$\frac{\partial x2}{\partial \tau} = \frac{C_{x_2x_1}C_{nn} - C_{nx_1}C_{x_2n}}{-C_{x_1n}^{2}C_{x_2x_2} + 2C_{x_1x_2}C_{x_1n}C_{x_2n} - C_{x_1x_2}^{2}C_{nn} - C_{x_1x_1}\left(C_{x_2n}^{2} - C_{x_2x_2}C_{nn}\right)} \quad (4)$$

As required by the convexity of the maximization problem, the denominators are negative. The sign of the numerator in Eq. (3) is also negative. Thus, the sign of the Eq. (3) is positive, which implies that a tariff on commodity 1 increases it's domestic production. The sign of the numerator in the Eq. (4) is ambiguous and depends on the sign of $C_{x_1x_2}$, which dictates the complement/substitute relationship between x_1 and x_2. If $C_{x_1x_2} < 0$, then the two agricultural commodities are complements and the numerator of the Eq. (4) is positive. However, if $C_{x_1x_2} > 0$, then the sign of the Eq. (4) is ambiguous. Hence, the tariff on the major imported commodity can either decrease or increase production of other commodities.

Likewise, we obtain the effect of the tariff on the nitrogen use (and nitrogen loss) as follows:

$$\frac{\partial n}{\partial \tau} = \frac{C_{x_1n}C_{x_2x_2} - C_{x_1x_2}C_{x_2n}}{-C_{x_1n}^{2}C_{x_2x_2} + 2C_{x_1x_2}C_{x_1n}C_{x_2n} - C_{x_1x_2}^{2}C_{nn} - C_{x_1x_1}\left(C_{x_2n}^{2} - C_{x_2x_2}C_{nn}\right)} \quad (5)$$

The sign of the Eq. (5) is ambiguous and depends on the substitute/complement relationship between the production of the two commodities. If $C_{x_1x_2} < 0$, the numerator is positive. Otherwise the numerator can be positive or negative. Hence, the effect of the tariff on nitrogen use can also be positive or negative. In China, soybean-corn rotation is widely practiced, and for these two commodities $C_{x_1x_2}$ is likely to be negative, implying a positive Eq. (5). In this setting, fertilizer use and N loss are likely to increase because corn is the most N-intensive crop. However, in our theoretical model, x_2 includes a group of commodities that may be substitutes or complements for x_1. In the case of x_2 being a substitute that is more (less) N-intensive than soybean, fertilizer use and N loss decline (increase) with an increase in the tariff on e_1. Hence, the effect of the tariff on nitrogen loss is indeterminate and should be examined empirically. These relationships can also be regionally heterogeneous.

3. Empirical model

We develop a multiple-region, multiple-product, price endogenous partial equilibrium model for Chinese agricultural sector to empirically examine the effect of trade tariffs on crop production and nitrogen use/

[1] This assumption is made for the sake of parsimony and is consistent with US-China agricultural trade context where soybean is overwhelmingly the top crop imported from US to China (USDA FAS, 2021). In relative terms, tariffs on other crops have negligible direct effects on production (Yao et al., 2021). Therefore, we aggregate production activities in China into two groups with the major imported group subject to the tariff.

loss in China. The model is structured following McCarl and Spreen (1980) and McCarl (1982). Price endogenous partial equilibrium models have been widely used for agricultural policy evaluation in various contexts (McCarl and Schneider, 2001; Egbendewe-Mondzozo et al., 2013; Havlík et al., 2011; Xu et al., 2022).

Our partial equilibrium model includes spatially explicit province-scale planted crop hectares, per ha N use and irrigation in China. Province scale planting and production decisions, including per ha N and irrigation use, generate regional crop output estimates. Cumulative output across regions forms national supply, which is combined with national demand and import/export specifications to produce corresponding prices. The model endogenously identifies optimal province-scale crop planting and associated production decisions to maximize consumer and producer surplus (Xu et al., 2022; Elbakidze et al., 2022).

The objective function in Eq. (6) maximizes the sum of producer and consumer surplus in China, subject to resource and technological constraints. Following Havlík et al. (2011), Chen et al. (2014), Yi et al. (2018) and Xu et al. (2022), the objective function is formulated as follows:

$$\max_{D_g, A_g} \Omega = \sum_{g} \int_{g} \varphi^{d}\left(D_g\right) d(.) - \sum_{i,g} NFC_{i,g} - \sum_{i,g} WC_{i,g} - \sum_{i,g} EC_{i,g} * A_{i,g} - \sum_{g,\tau} \left(p_g + \tau\right) Q_{g,s}^{im}(\tau) \tag{6}$$

where Ω is cumulative consumer and producer benefits in g agricultural commodity markets; φ^d is the inverse demand function and D_g is domestic consumption of commodity g. i denotes the provinces in China. $NFC_{i,g}$ and $WC_{i,g}$ are costs of nitrogen fertilizer and water for crop g in region i respectively. $EC_{i,g}$ is the production cost, excluding nitrogen fertilizer and water. $A_{i,g}$ is the acreage of crop g in region i with n kg nitrogen fertilizer use and w water use per hectare. p_g is the corresponding international prices. τ is the tariff imposed on U.S. soybeans. $Q_{g,s}^{im}(\tau)$ is imports from region s as functions of the tariff imposed on the US soybean, τ. s refers to the source region of imports (US and ROW).

The model constraints include supply and demand balance, planted acreage, cost equations and water use.

$$D_g + Q_g^{ex} \le \sum_i Y_{i,g} * A_{i,g} + \sum_s Q_{g,s}^{im} \forall g \tag{7}$$

$$NFC_{i,g} = \theta_{i,g} * A_{i,g} \forall i, g \tag{8}$$

$$WC_{i,g} = \pi_{i,g} * A_{i,g} \forall i, g \tag{9}$$

$$\sum_g A_{ig} w_{ig} < \overline{w_i} \forall i \tag{10}$$

$$A_{i,g} = \sum_m \tau_{mi} * h_{igm} + \sum_n \gamma_{ni} * s_{ign} \forall i, g \tag{11}$$

$$\sum_m \tau_{mi} + \sum_n \gamma_{ni} = 1 \forall i \tag{12}$$

Eq. (7) represents the crop supply and demand balance, where Y_{ig} is the per ha yield of crop g with nitrogen application n and water use w in region i. $Q_{g,s}^{im}$ is the impot of commodity g. Eq. (8) determines nitrogen cost for crop g in region i, where $\theta_{i,g}$ is the nitrogen fertilizer cost per ha. Similarly, Eq. (9) computes cost of irrigation water, where $\pi_{i,g}$ is the cost of water per ha for crop g in region i. Eq. (10) is the water use constraint, where $w_{i,g}$ is the water use per ha of crop g in region i and $\overline{w_i}$ is the maximum agricultural water supply per province.

Eqs. (11) and (12) restrict land allocation in region i for crop g, using a convex crop mix constraint that implicitly captures crop acreage restrictions such as technical, management and policy factors. The specification binds acreage within the historically observed lower and upper bounds (Chen and Önal, 2012). In Eq. (11), the planted area of crop g in province i, is the sum of the weighted historical crop acreages. h_{igm} and s_{ign} are the historical and synthetic planted areas, respectively; τ_{mi} and γ_{ni} are the endogenously determined crop acreage portfolio weights; m and n are the sets of "historical" acreage observations and synthetic acreage data. Eq. (12) constrains the sum of τ_{mi} and γ_{ni} to be equal to 1, assuring that the endogenously determined regional crop acreages are convex combinations of acreages observed in the past and acreages simulated synthetically.

Nitrogen fertilizer use inevitably leads to nitrogen loss. Nitrogen loss in this study refers to nitrogen leaching and runoff due to fertilizer use. Estimates of surface nitrogen losses from crop production are obtained by multiplying the amount of nitrogen fertilizer use by the corresponding loss coefficient (Xia et al., 2018). We estimate nitrogen loss in nitrogen fertilizer use following Ti et al. (2012) and Xia et al. (2018):

$$NL_{i,g} = \left[\left(RO_{i,g} + LE_{i,g}\right) / AE_{i,g}\right] * NF_{i,g} * A_{i,g} \tag{13}$$

where NL is estimated nitrogen loss. $RO_{i,g}$ is nitrogen runoff loss rate, $LE_{i,g}$ is nitrogen leaching loss rate, and $AE_{i,g}$ is the nitrogen fertilizer use efficiency. $NF_{i,g}$ is per ha nitrogen use.

4. Data source

The study area includes 31 provinces in mainland China. Soybean, wheat, corn, peanuts, and rapeseed are widely planted major crops in China, covering >70% of the country's cultivated land. Agricultural production data including cultivation area by province in 2018 are from the "China Statistical Yearbook" and "National Database" of the National Bureau of Statistics (NBS) (https://data.stats.gov.cn). Consumption of major agricultural commodities, including diets, feed, industrial use, seed, food loss and waste in the baseline year is from "China BRIC Agricultural Database" (http://www.chinabric.com/). The production inputs (land, labor, fertilizer, pesticides, water, and others) are obtained from the "National Compilation of Data on Costs and Returns of Agricultural Products" (NDRC, 2020). The nitrogen loss coefficients for different crops on farmland were taken from Ti et al. (2012), with nitrogen leaching loss coefficients of 3.4% for paddy fields and 11.1% for drylands, and N runoff loss coefficients of 5% for both paddy and drylands.

We use the production, consumption, and price data from 2018 as the baseline. We calibrate the model to match observed data for 2018 using the positive mathematical programming (PMP) approach (Howitt, 2014). After calibration, the results of model simulation including province scale crop acreages, yield, fertilizer use, and nitrogen losses are within 5% of the observed data (Table 1). For example, the observed wheat harvest in 2018 was 24.47 million ha, while the baseline simulated area is 24.03 million ha, an underestimation of 0.98%. In terms of model validation, it is reassuring that the solutions are close to the observed values, suggesting that the model provides a reasonable baseline representation for further analysis. he model results do not match the values in 2018 perfectly because model solutions represent the long-run equilibrium rather than circumstances in any particular year.

We vary tariff rates on soybeans originating from the US and examine the impacts on agricultural production and N loss in China. Specifically, in addition to the baseline with no additional tariff on soybean imports from US (0%), we present results from six tariff scenarios incrementally increasing by 5% from 0% to 30%. Thus, this study includes seven simulation scenarios, namely scenario 0%, scenario 5%, scenario 10%, scenario 15%, scenario 20%, scenario 25% and scenario 30%.

5. Results

The corresponding results for crop imports, planted acreages, production, fertilizer use, and nitrogen runoff are presented below.

Table 1
Comparison between observed and model-generated data in 2018.

	Acreage (million ha)		Yield (million t)		Fertilizer use (million t)		N loss (million t)	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Wheat	24.27	24.03 (−0.98%)	13.02	12.96 (−0.45%)	9.92	9.81 (−1.07%)	0.78	0.77 (−1.48%)
Corn	42.13	42.12 (−0.03%)	25.87	25.94 (0.28%)	14.61	14.51 (−0.67%)	1.17	1.15 (−1.42%)
Soybean	8.41	8.09 (−3.83%)	1.65	1.69 (2.58%)	0.89	0.87 (−2.26%)	0.05	0.05 (−1.57%)
Peanut	4.63	4.44 (−3.97%)	1.74	1.74 (0.00%)	1.41	1.38 (−1.93%)	0.08	0.08 (−1.11%)
Rapeseed	6.55	6.27 (−4.27%)	1.32	1.32 (−0.17%)	1.49	1.50 (0.28%)	0.12	0.12 (−0.94%)

Note: % in parentheses are the deviations between model simulated results and actual observed values in 2018.

5.1. Crop import

Table 2 presents the aggregate crop import results, along with a breakdown of soybean solutions into imports from US and ROW. As expected, soybean imports decrease as tariff on US soybean increases. Since the trade tariffs are imposed only on US soybean, imports shift from US to ROW. However, the substitution is not one-to-one. The decrease in US soybean imports is offset by a combination of increased imports from other trade partners and increased domestic production, which is likely to impact regional N loss in China. We observe that corn imports also decrease with higher tariffs on US soybean. Corn imports decrease because more corn is produced domestically as corn and soybean are often planted in rotation as completements. Conversely, imports of wheat, peanut, and rapeseed increase when soybean tariff increases. These imports increase because of decrease in domestic production as acreages shift to soybean and corn.

China's soybean imports decrease by 3% from 95.53 million t in the baseline scenario to 92.68 million t in the 30% tariff scenario. The imports of wheat and corn are more sensitive to soybean tariff. China's wheat imports increase to 7.74 million t if soybean tariff researches 30%, which is >80% higher than imports in the baseline scenario. China is a corn importer if there is no trade barrier. However, if the tariff goes up to 20%, China starts to export corn. The effects of US soybean tariff on peanuts and rapeseed are relatively small, with imports increasing by up to 1.5% and 3% respectively in the highest tariff scenario.

5.2. Cultivated area and production

Table 3 presents changes in major crop acreages in China across tariff scenarios. Soybean acreage increases by 1.46 million ha (18.05%) from 8.09 to 9.55 million ha when tariff on the US soybean increases to 30%. Corn hectares also increase by 0.81 million ha (2%) because soybean and corn are often planted in rotation. Hence, an increase in soybean hectares comes with an increase in corn hectares. Wheat planting, however, goes down by 3.16% from 24.027 million ha to 23.269 million ha. Wheat and soybean growing seasons in China overlap, which implies competitive land allocation. Hence, soybean and corn displace wheat planting. These results are consistent with Table 2, as increased wheat imports substitute part of the domestic wheat supply. The effects on rapeseed and peanut acreages are small, as both change by < 1% even in the highest tariff scenario. Cumulatively, the results show that with a 25% tariff on US soybean, planting of major crops increases by 1.37% from 84.9 to 86.1 million ha.

Table 4 illustrates production changes in different tariff scenarios. Consistent with the estimated increase in the planted hectares, China's soybean production increases significantly. A 10% tariff on the US soybean results in a 3.44% growth in China's soybean production, while a 30% tariff increases domestic production by 17.9% to 2.85 million t. The loss of soybean imports from the US is substituted with increased domestic production and imports from ROW. Corn production increases while wheat, peanuts and rapeseed production decreases in response to higher soybean import tariffs, consistent with the changes in planted hectarage.

5.3. Fertilizer use and nitrogen loss

The increases (decreases) in the domestic production of soybean and corn (wheat, peanut, and rapeseed) imply changes in associated input use including nitrogen fertilizer. Greater production of corn has a positive effect on nitrogen use while peanut, rapeseed and wheat reductions imply less nitrogen use. As soybean and corn hectarages substitute crops like wheat, rapeseed and peanut the effects on fertilizer use and losses are ambiguous because soybean is least N-intensive while corn is most N-intensive. Moreover, the changes in nitrogen use and losses are

Table 2
Major crop imports to China (million t).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	95.53	95.31 (−0.23%)	94.99 (−0.57%)	94.56 (−1.02%)	94.03 (−1.57%)	93.41 (−2.23%)	92.68 (−2.99%)
-from US	32.85	29.06 (−11.54%)	25.27 (−23.08%)	21.48 (−34.62%)	17.69 (−46.17%)	13.90 (−57.71%)	10.10 (−69.25%)
-from ROW	62.68	66.250 (5.69%)	69.72 (11.22%)	73.08 (16.59%)	76.35 (21.80%)	79.51 (26.85%)	82.57 (31.73%)
Wheat	4.30	4.91 (14.39%)	5.52 (28.38%)	6.10 (41.96%)	6.67 (55.13%)	7.21 (67.89%)	7.74 (80.25%)
Corn	2.83	2.06 (−27.05%)	1.32 (−53.33%)	0.60 (−78.85%)	−0.10 (−103.60%)	−0.78 (−127.58%)	−1.44 (−150.80%)
Peanut	0.25	0.25 (0.26%)	0.25 (0.51%)	0.25 (0.76%)	0.25 (1.00%)	0.25 (1.23%)	0.26 (1.45%)
Rapeseed	4.75	4.77 (0.50%)	4.80 (0.99%)	4.82 (1.46%)	4.84 (1.92%)	4.86 (2.37%)	4.88 (2.80%)

Note: tariff refers to China's increased tariffs on US soybean imports; % in parentheses are the deviations between the results of baseline and different tariff scenarios.

Table 3
Cultivated area in China (million ha).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	8.09	8.21	8.39	8.62	8.91	9.22	9.55
		(1.50%)	(3.68%)	(6.53%)	(10.07%)	(13.91%)	(18.05%)
Wheat	24.03	23.86	23.70	23.57	23.46	23.36	23.27
		(−0.69%)	(−1.36%)	(−1.92%)	(−2.35%)	(−2.76%)	(−3.16%
Corn	42.12	42.26	42.43	42.60	42.75	42.87	42.98
		(0.35%)	(0.74%)	(1.14%)	(1.50%)	(1.78%)	(2.04%)
Peanut	4.44	4.44	4.44	4.44	4.44	4.44	4.44
		(0.00%)	(−0.01%)	(−0.01%)	(−0.02%)	(−0.02%)	(−0.02%)
Rapeseed	6.27	6.26	6.25	6.24	6.23	6.22	6.21
		(−0.17%)	(−0.34%)	(−0.50%)	(−0.65%)	(−0.81%)	(−0.95%)
Total	84.95	85.04	85.21	85.46	85.79	86.11	86.45
		(0.11%)	(0.31%)	(0.61%)	(0.99%)	(1.37%)	(1.77%)

Note: tariff refers to China's increased tariffs on US soybean imports; % in parentheses are the deviations from the baseline scenario.

Table 4
Crop Production in China (million tons).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	15.97	16.19	16.52	16.94	17.47	18.10	18.83
		1.40%	3.44%	6.11%	9.40%	13.34%	17.90%
Wheat	131.44	130.82	130.22	129.64	129.07	128.52	127.99
		−0.47%	−0.93%	−1.37%	−1.80%	−2.22%	−2.62%
Corn	257.18	257.94	258.68	259.40	260.10	260.78	261.44
		0.30%	0.59%	0.87%	1.14%	1.40%	1.66%
Peanut	17.35	17.35	17.35	17.35	17.35	17.34	17.34
		0.00%	−0.01%	−0.01%	−0.01%	−0.02%	−0.02%
Rapeseed	13.28	13.25	13.23	13.21	13.18	13.16	13.14
		−0.18%	−0.35%	−0.52%	−0.69%	−0.85%	−1.00%

spatially heterogeneous. We present the aggregate and regional nitrogen use and loss impacts below.

Table 5 shows compound fertilizer use results across five soybean tariff scenarios. Nitrogen fertilizer use results can be found in Appendix 1. As soybean tariff on imports from the US increases from 0% to 30%, compound fertilizer uses increases in soybean and corn production and decreases in wheat and rapeseed production. Soybean is the least N-intensive crop among the five modeled in this study. Nevertheless, greater soybean acreage and production results in an increased fertilizer use for soybean production relative to the baseline. Soybean nitrogen use increases from 0.866 million tons in the baseline to 1.07 million tons in the highest tariff, a 23.75% increase. As expected, nitrogen use also increases in corn production. Percentage increase in corn nitrogen use (up to 2.24%) is smaller than in soybean. However, in absolute terms, nitrogen use increase in corn production (324 thousand t) is greater than in soybean production because corn is more fertilizer intensive than soybean. Fertilizer use in wheat production decreases from 9.81 to 9.53 million tons as tariffs on US soybeans increase to 30%. Peanut fertilizer use is almost unchanged. Cumulatively, nitrogen fertilizer use increases by <1 %.

Table 6 shows nitrogen loss results, which are consistent with compound fertilizer use trends in Table 5. Nitrogen loss increases in soybean and corn production and decreases in production of other crops. Nitrogen loss in soybean production increases by 23.26% in the 30% tariff scenario, generating almost 12 thousand additional tons of surplus nitrogen. Corn nitrogen surplus increases by up to 35 thousand t, which is a 3.05% increase relative to the baseline. Wheat and rapeseed nitrogen losses decrease as acreage, production and fertilizer use in these crops decrease. Nitrogen surplus in peanut production is almost unaffected. Cumulatively, nitrogen losses increase by up to 1% in the 30% tariff scenario.

Regional nitrogen loss changes in the 25% tariff scenario relative to the baseline are provided in Fig. 1 (tons) and Fig. 2 (percentage). The results show that nitrogen loss increases in all provinces, but the changes vary significantly across regions ranging between 5 t and 4592 t. In percentage terms, these increases range from 0.05% to 2.97% increase in N loss. The largest increases in nitrogen loss are observed in Northeast China (including Heilongjiang, Jilin, and Liaoning) and Inner Mongolia. These are the top soybean and corn producing provinces in China. Nitrogen use in these areas is high and the variation in nitrogen loss is also

Table 5
Fertilizer use in China (thousand t).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	866.06	884.85	912.14	947.83	992.03	1032.20	1071.76
		2.17%	5.32%	9.44%	14.54%	19.18%	23.75%
Wheat	9810.59	9761.88	9714.64	9667.35	9620.08	9574.27	9529.91
		−0.50%	−0.98%	−1.46%	−1.94%	−2.41%	−2.86%
Corn	14,507.67	14,561.79	14,614.31	14,664.42	14,716.06	14,774.99	14,832.04
		0.37%	0.74%	1.08%	1.44%	1.84%	2.24%
Peanut	1377.92	1377.86	1377.81	1377.74	1377.69	1377.64	1377.59
		0.00%	−0.01%	−0.01%	−0.02%	−0.02%	−0.02%
Rapeseed	1498.00	1495.02	1492.13	1489.32	1486.59	1483.95	1481.30
		−0.20%	−0.39%	−0.58%	−0.76%	−0.94%	−1.11%
Total	28,060.23	28,081.40	28,111.03	28,146.67	28,192.45	28,243.04	28,292.60
		0.08%	0.18%	0.31%	0.47%	0.65%	0.83%

Note: tariff refers to China's increased tariffs on US soybean imports; % in parentheses are the deviations relative to the baseline scenario.

Table 6
N losses in China (thousand t).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	50.14	51.23	52.83	54.91	57.49	59.94	61.80
		2.19%	5.36%	9.52%	14.66%	19.56%	23.26%
Wheat	767.67	764.14	760.71	756.82	752.40	748.11	743.96
		−0.46%	−0.91%	−1.41%	−1.99%	−2.55%	−3.09%
Corn	1149.65	1156.21	1162.14	1167.53	1173.02	1178.95	1184.69
		0.57%	1.09%	1.56%	2.03%	2.55%	3.05%
Peanut	79.94	79.93	79.93	79.93	79.92	79.92	79.92
		0.00%	−0.01%	−0.01%	−0.02%	−0.02%	−0.03%
Rapeseed	122.58	122.31	122.05	121.80	121.56	121.33	121.09
		−0.22%	−0.43%	−0.63%	−0.83%	−1.02%	−1.21%
Total	2169.97	2173.83	2177.66	2180.99	2184.40	2188.25	2191.46
		0.18%	0.35%	0.51%	0.66%	0.84%	0.99%

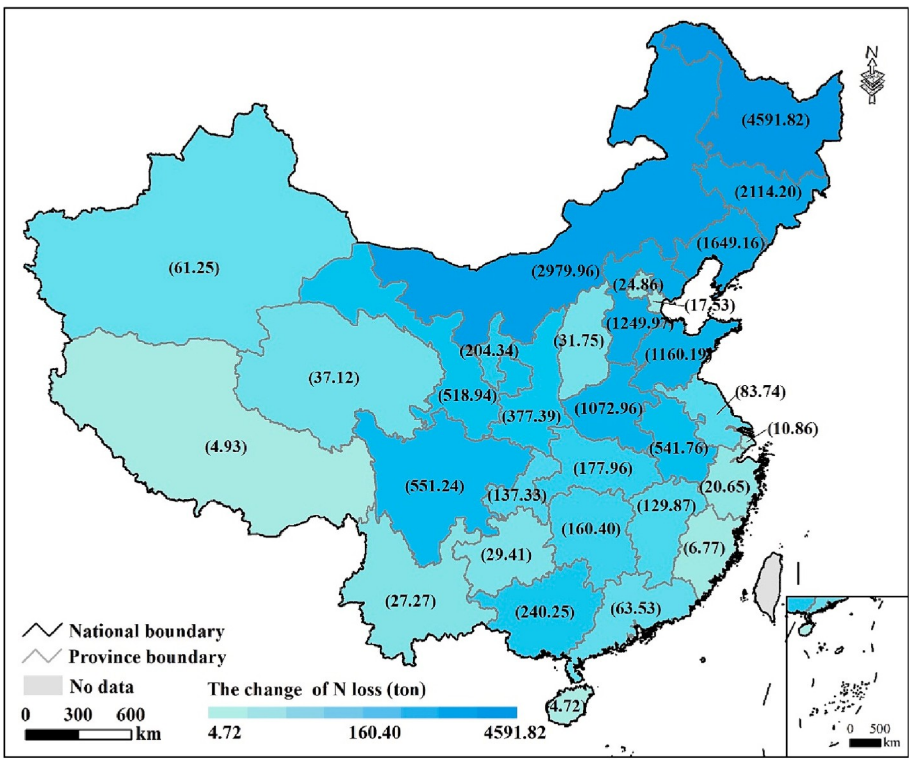

Fig. 1. N loss increase in the 25% tariff scenario on soybean imported from US.

higher than the national average. Hence an increase in nitrogen loss poses a greater threat to the environment in these provinces. Nitrogen loss in Hebei, Henan and Shandong in central China are average across provinces. Some provinces in southern China, such as Hainan, Guangxi, and Jiangxi, have relatively low nitrogen use. Thus, total nitrogen loss increase of these province is low, despite high rates of nitrogen loss.

6. Discussion

International agricultural trade plays a pivotal role in ensuring global food security. Food and agricultural commodity imports are particularly crucial in regions such as China, where there is limited arable land and food demand is growing. Numerous studies have assessed the impact of agricultural trade on agricultural land use savings in China. For instance, China's grain imports have saved 62.25 million ha of agricultural land use annually between 2002 and 2020. The imports of soybean and wheat account for most of the land use savings (Cao and Yuan, 2022). Over the past five decades, international agricultural trade has significantly enhanced global land use efficiency and saved approximately 2270 million hectares of agricultural land (Bai et al., 2022).

Although the benefits of international trade have been well recognized, concerns about the impacts on environmental quality have also been raised (Bajona and Kelly, 2012; Shi et al., 2016). Intuitively, international agricultural trade can benefit the environmental quality of the importing countries at the potential expense of the exporting countries (Martinez-Melendez and Bennett, 2016). Shi et al. (2016) conclude that China's total nitrogen utilization in agricultural production is significantly lower with international trade than without. However, trade can also have an opposite effect in some contexts due to crop heterogeneity in fertilizer use intensity. For example, domestic environmental quality may suffer from importing low nitrogen intensity crops like soybean if domestic soybean production is replaced with relatively more nitrogen intensive crops like wheat (Oita et al., 2016; Martinez-Melendez and Bennett, 2016; Sun et al., 2018). Hence, the effect of trade on the importing country's environmental quality can be theoretically ambiguous.

We illustrate the relationship between international agricultural trade and environmental impacts in China by empirically examining the effect of a bilateral trade barrier on nitrogen loss. Our illustrative

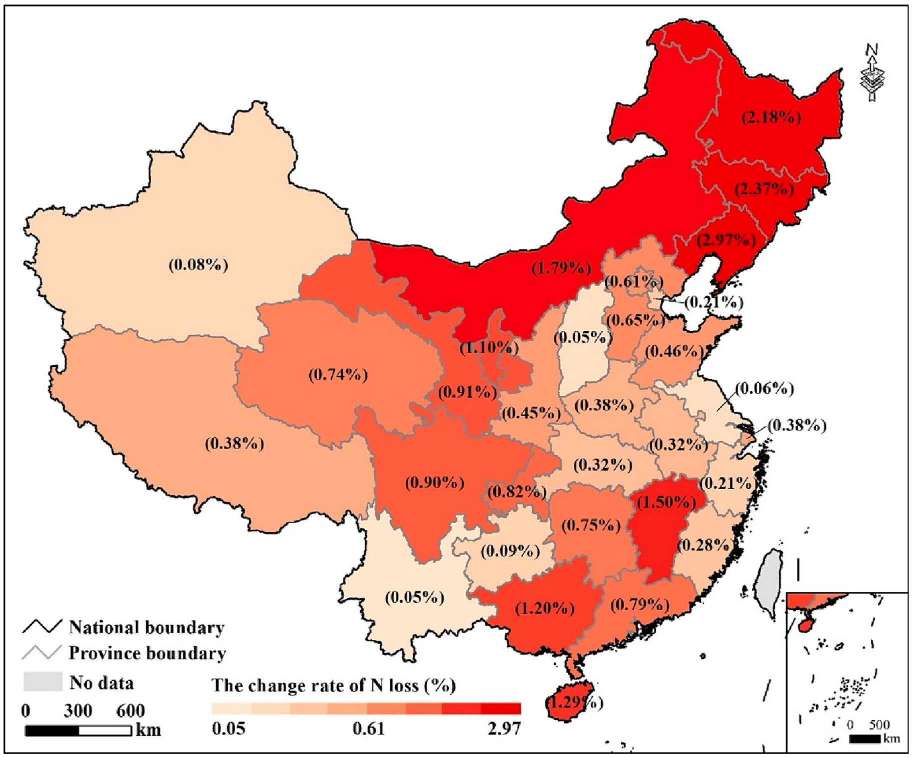

Fig. 2. N loss percentage increase in the 25% tariff scenario on soybean imported from US.

scenario resembles the 2018 trade conflict where China imposed a 25% retaliatory tariff on agricultural commodities imported from the US. We focus on the effects of a potential structural change rather than a temporary trade barrier. We show that a tariff on the US soybeans significantly reduces soybean imports from the US and increases the imports from the rest of the world. However, the increase in ROW imports does not entirely offset the decrease in US imports. Hence, soybean acreage and production in China increase. Corn acreage and production in China also increase because soybean and corn are often planted in rotation. The increases in soybean and corn acreages and production come with greater nitrogen fertilizer use and loss relative to the baseline scenario with no tariff on soybean imports from the US. The marginal decrease in nitrogen surplus from the decrease in wheat, peanut, and rapeseed production does not offset the N loss increase in corn and soybean production. As a result, cumulative N loss in China increases.

We document that a tariff on US soybean, the dominant import commodity in China, increases domestic acreage and production, displacing some of the acreage of other crops like wheat. This substitution decreases nitrogen use and surplus because soybean is less N-intensive than wheat. However, soybean is often planted in rotation with corn. Therefore, corn acreage also increases alongside soybean, which positively affects N use and loss.

We find that N use and surplus increase relative to the baseline scenario. The effects of the tariff on N loss are heterogeneous across regions. In the scenario with a 25% tariff on US soybeans, the increase in N loss across provinces in China ranges between 0.05% and 3%. Hence, the impact of a 25% tariff on US soybean on N runoff in Chinese provincial regions is small in relative terms. However, even a relatively small increase of 3% in N runoff can harm sensitive ecosystems. Liu (2017) found that excessive nitrogen fertilizer use in China is concentrated in North China (Neimenggu, Hebei, Henan, Shangdong) and South China (Guangdong and Hainan). Our results show that a soybean import tariff has greatest impact on nitrogen fertilizer loss in these two areas.

Our results show a small but negative effect of international trade friction on environmental outcomes. The positive effect of free trade on environmental quality is consistent with other studies. Using data on food production and trade between China and 26 other countries, Shi et al. (2016) estimate that agricultural trade greatly reduced nitrogen pollution in China. Liu et al. (2020) show that a trade conflict between US and China increases global CO_2 emissions. Yao et al. (2021) indicate that China would have generated a 1.8 Tg nitrogen surplus if its crop portfolio imported from the US had been produced domestically. Lu et al. (2022) also shows that multilateral trade between China and Central Asian countries reduces nitrogen and phosphorus surplus in agricultural production. We complement these studies by providing evidence in support of the positive, though arguably small, impact of free trade on environmental quality in China relative to trade with a tariff on largest imported commodity from the US.

Several caveats of this study need to be made clear. First, the model provides optimal production and consumption solutions from the perspective of a centralized decision maker and does not account for individual producer decision making nuances. This limitation is less pertinent in the context of China than other countries, for which these types of models have been used extensively (Xu et al., 2022; Elbakidze et al., 2022; McCarl and Schneider, 2001). Second, the model includes only five major commodities produced in China. In this respect, the model does not fully represent land use in China and provides a lower bound of N loss. However, the omitted crops are not likely to cause a significant bias in the estimates of the changes in nitrogen loss because the crops included in the model are most relevant in terms of land use and N surplus. Third, the model represents a long-run equilibrium solution rather than the short-term land and nitrogen use changes in response to a trade shock. Therefore, the model is not suitable for evaluating short term impacts of a one-time trade shock on land and fertilizer use. Instead, the solutions are best interpreted as long run responses to a structural change in trade arrangements.

7. Conclusion and policy implication

Our research makes a valuable contribution to the existing body of literature by investigating the nutrient runoff impacts of an agricultural trade barrier between the two largest trading partners, the US and China. Specifically, we examine how a tariff imposed by China on soybean imports from the US affects cropland nitrogen loss in China. The results provide evidence in support of small but negative effect of an agricultural trade barrier on environmental quality in China, complementing the findings in recent literature (Yao et al., 2021; Lu et al., 2022; He et al., 2019).

The results show that the tariff on soybean imports from the US decrease imports and increase domestic soybean and corn production in China. While there is a decline in the planting and production of other crops, the overall cropland in China expands due to greater corn and soybean planting. Hence, trade barriers on primary agricultural commodities affect crop production and increase environmental risks, even in the importing country.

Our study reveals a complex interplay of factors resulting from reduced soybean imports. On the one hand, the decline in imports prompts an increase in domestic soybean production, displacing the cultivation of more nitrogen-intensive crops like wheat. This displacement reduces N surplus. However, corn planting and production increase due to the soybean-corn rotation practices often employed in China. The augmented production of soybean and corn leads to greater fertilizer usage and increased nitrogen loss. The reduction in fertilizer uses and N loss from decreased production of other crops is modest in comparison to the N use increase in corn and soybean production. Hence, these changes have a net positive effect on nitrogen loss because corn is the most N-intensive commodity and its domestic production increases significantly in response to the barrier on soybean imports. The expansion of soybean and corn planting exceeds the decrease in other crops. Consequently, the cumulative N loss grows when a trade barrier impedes soybean imports.

We show that the effects of the tariff on N losses are heterogeneous across regions. In the scenario with a 25% tariff on US soybeans, the increase in N loss across provinces in China ranges between 0.05% and 2.97%. Northeastern China, which includes China's main soybean-producing regions, experiences a greater N loss than other regions in China.

A couple of policy implications can be derived from the study results. Firstly, China should continue to promote its agricultural import diversification strategy, enhance the resilience of its agricultural supply, and mitigate the adverse impact of trade frictions on the agricultural environment. Secondly, there is a need to coordinate agricultural trade policy with nitrogen emission policymaking and to synergize the management of agricultural imports and agri-environmental objectives. Thirdly, nitrogen fertilizer uses to crops needs to be regulated in a categorized approach, with particular attention to the regulation of nitrogen fertilizer use to agricultural products that are highly affected by international trade.

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Authors' contributions

Juanli Wang analysis the data and drafted the work; Levan Elbakidze devekoped the method and reviewed the manuscript; Shuao Yu analysis the data; Yaru Xin collected the data; Shixiong Song drew figures and tables; Ma designed the conception and reviewed the manuscript.

Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Appendix A. Appendix

Appendix 1
Nitrogen fertilizer use in China (thousand ton).

Tariff	0%	5%	10%	15%	20%	25%	30%
Soybean	311.41	318.23	328.12	341.06	357.08	372.33	383.84
		2.19%	5.36%	9.52%	14.66%	19.56%	23.26%
Wheat	4768.15	4746.21	4724.90	4700.75	4673.27	4646.65	4620.87
		−0.46%	−0.91%	−1.41%	−1.99%	−2.55%	−3.09%
Corn	7140.66	7181.43	7218.25	7251.75	7285.87	7322.68	7358.33
		0.57%	1.09%	1.56%	2.03%	2.55%	3.05%
Peanut	496.51	496.49	496.47	496.44	496.42	496.40	496.38
		0.00%	−0.01%	−0.01%	−0.02%	−0.02%	−0.03%
Rapeseed	761.34	759.69	758.10	756.54	755.03	753.57	752.12
		−0.22%	−0.43%	−0.63%	−0.83%	−1.02%	−1.21%
Total	13,478.08	13,502.05	13,525.85	13,546.55	13,567.68	13,591.64	13,611.54
		0.18%	0.35%	0.51%	0.66%	0.84%	0.99%

Appendix 2

Nitrogen loss by province under the scenario 25% (ton).

	Baseline	Add 25% tariff	Dev	%Dev
Anhui	167,848.68	168,390.44	541.76	0.32%
Beijing	4105.33	4130.19	24.86	0.61%
Chongqing	16,779.22	16,916.55	137.33	0.82%
Fujian	2397.25	2404.02	6.77	0.28%
Gansu	57,174.23	57,693.18	518.94	0.91%
Guangdong	8037.53	8101.06	63.53	0.79%
Guangxi	19,993.08	20,233.33	240.25	1.20%
Guizhou	32,145.32	32,174.73	29.41	0.09%
Hainan	366.07	370.80	4.72	1.29%
Hebei	191,154.64	192,404.61	1249.97	0.65%
Heilongjiang	211,045.28	215,637.10	4591.82	2.18%
Henan	283,260.05	284,333.04	1072.99	0.38%
Hubei	55,257.13	55,435.09	177.96	0.32%
Hunan	21,492.98	21,653.38	160.40	0.75%
Jiangsu	135,773.24	135,856.98	83.74	0.06%
Jiangxi	8643.26	8773.13	129.87	1.50%
Jilin	89,377.51	91,491.71	2114.20	2.37%
Liaoning	55,499.56	57,148.72	1649.16	2.97%
Neimenggu	166,041.65	169,021.62	2979.97	1.79%
Ningxia	18,566.23	18,770.57	204.34	1.10%
Qinghai	4989.31	5026.42	37.12	0.74%
Shaanxi	83,606.88	83,984.27	377.39	0.45%
Shandong	251,224.47	252,384.66	1160.19	0.46%
Shanghai	2812.34	2823.20	10.86	0.39%
Shanxi	62,470.63	62,502.38	31.75	0.05%
Sichuan	60,931.44	61,482.68	551.24	0.90%
Tianjin	8491.33	8508.86	17.53	0.21%
Tibet	1282.16	1287.09	4.93	0.38%
Xinjiang	78,984.84	79,046.09	61.25	0.08%
Yunnan	60,183.12	60,210.39	27.28	0.05%
Zhejiang	10,037.09	10,057.74	20.65	0.21%

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