

U.S.-China Agricultural Trade and Environmental Outcomes: The Case of Nutrient Runoff to the Gulf of Mexico

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Abstract

We quantify the relationship between nitrogen (N) runoff to the Gulf of Mexico, U.S. agricultural production, and exports to China using an integrated assessment model. We show that a 25% Chinese tariff on U.S. soybean and corn increases annual N runoff to the Gulf by 800 metric tons (0.2%) as soybean production in the Mississippi River Basin is displaced with more N-intensive crops. Results also indicate that reducing N runoff to the Gulf by 10% decreases U.S. corn export to China by 14.5%, similar to the effect of a 25% Chinese tariff on corn and soybeans.

Keywords: Trade war, Nitrogen runoff, Economic optimization, Agricultural production

1. Introduction

The U.S. is the largest producer and exporter of agricultural commodities. From 1990 to 2020, U.S. agricultural exports grew from \$39.3 billion to \$146 billion. Trade between the U.S. and China, one of the top U.S. trade partners, increased from \$0.8 to \$26.4 billion (USDA FAS, 2021a). Agricultural production involves significant environmental externalities, including degradation of downstream water quality (Khanna and Shortle, 2017; Shortle et al., 2021). Nitrogen (N) runoff to the Gulf of Mexico has long been a complex challenge for U.S. regulators and industry. Yet, the interdependencies between agricultural trade policy, production, land use, and downstream water quality in the Gulf of Mexico have yet to be quantified.

The intensive fertilizer use in agricultural production and growing agricultural exports raised significant concerns about the implications for environmental quality in the U.S. (Kirchner and Schmid, 2013; Oita et al., 2016; Henderson and Lankoski, 2020). Yet, there is a lack of empirical literature on the interdependence between agricultural trade, production, and nutrient runoff externalities (van Veen-Groot and Nijkamp, 1999; Balogh and Jámor, 2020). Yao et al. (2021) document the effect of U.S.-China trade friction on regional nutrient surplus and water resource depletion in the U.S. They find that trade barriers mainly affect soybean production and export. They do not, however, evaluate the impacts on nutrient runoff to coastal waterbodies like the Gulf of Mexico. Hence, important research questions remain to be addressed. How sensitive is downstream agricultural nutrient runoff to trade policy and agricultural production? How does the spatial distribution of downstream nutrient runoff respond to trade policy? How do nutrient runoff reduction objectives affect agricultural trade?

Mississippi River Basin (MRB) is the largest watershed in the U.S. It includes some of the most productive agricultural regions where fertilizer use has significant implications for downstream water quality. Forty-one percent of N runoff to the Gulf of Mexico comes from agricultural fertilizer use in the MRB (Robertson and Saad, 2013). This nutrient runoff contributes to eutrophication and annual Hypoxic zone formation along the Texas, Louisiana, and Mississippi coasts (Shortle et al., 2021; US EPA, 2019). To reduce nutrient runoff to the Gulf, the U.S. Environmental Protection Agency (US EPA) established the Mississippi River/Gulf of Mexico Hypoxia Task Force in 2001, aiming to reduce the size of the Hypoxic zone to 5,000 km² by 2035 (US EPA,

2014). Still, the size of the “dead zone” reached 16,405 km² in 2021 (US EPA, 2022), and eutrophication in the northern Gulf of Mexico remains a “wicked challenge” (Shortle and Horan, 2017; Khanna et al., 2019).

Existing literature on agricultural trade and the environment is mostly focused on greenhouse gases and land transfer from forest to agriculture (Lee and Zhang, 2009; Saikku et al., 2012; DeFries et al., 2013; Jones et al., 2013; Blandford et al., 2014; Henders et al., 2015). Only a few studies examine the impact of agricultural trade on downstream water quality. Savard and Bohman (2003) combine an economic model of the North American hog sector with the Erosion Productivity Impact Calculator (EPIC) to assess the impacts of trade and environmental policies on water quality. Saunders and Cagatay (2004) examine trade liberalization among OECD members, the spatial distribution of N fertilizer use, feed use in dairy production, and nitrate pollution. The authors show that OECD trade liberalization reduces groundwater nitrate concentration in the E.U. but increases in other regions.

The significance of the U.S.-China soybean trade for nutrient externalities has been documented in Yao et al. (2021). Using a computable general equilibrium model, they show that agricultural trade barriers between the U.S. and China, similar to the recent trade conflict, have significant negative implications for nutrient surplus in agricultural production. They find that the loss of soybean export markets to China decreases planted acreage but increases N surplus and water use as production of less N-intensive soybeans in U.S. is replaced with more N-intensive crops. Our analysis confirms this result and contributes by quantifying the relationship between U.S. – China trade friction and N runoff to the Gulf of Mexico. We also explore the reverse impacts of reducing nutrient runoff to the Gulf of Mexico on agricultural trade between U.S. and China.

Examining the 2018 U.S.-China trade conflict and its impact on environmental quality is not this papers’ objectiveⁱ. Instead, the incident provides a supportive motivation for our study as an illustrative example of a trade barrier with potential environmental implications. In 2018, China levied tariffs on U.S. agricultural and food exports in response to U.S.-initiated tariffs on a range of Chinese products (CRS, 2018; Grant et al., 2021). A 25% tariff was imposed on U.S. agricultural imports (CRS, 2018) and planted soybean acreage in the U.S. decreased from 36.5 million ha in 2017 to 30.3 million ha in 2019 (USDA NASS, 2021a). Subsequent trade renegotiations have eased trade friction to some degree (Feenstra and Hong, 2022). Nevertheless, the incident

serves as a sign of growing protectionist sentiments in the international arena. Environmental implications of weakening international trade deserve additional research, especially if protectionist sentiments and policies continue to gain momentum and may have ramifications for environmentally sensitive ecosystems like the Gulf of Mexico.

This study uses the corn and soybeans market as a case study to examine the interdependencies between U.S.-China trade, agricultural production, and nutrient runoff to the Gulf of Mexico. Soybean (\$25.7 billion in 2020) and corn (\$9.2 billion in 2020) are some of the major U.S. agricultural export commodities (USDA FAS, 2021b). In 2020, soybeans and corn ranked 1st (\$14.2 billion) and 4th (\$1.2 billion) among U.S. agricultural exports to China in terms of market value, and the demand for these commodities is expected to remain high, barring trade frictions (USDA FAS, 2021a, b). Although soybean is a less N-intensive crop than others, a tariff on soybeans exports by a major importing partner can have a significant impact on fertilizer use and nutrient surplus in the U.S. (Yao et al. 2021).

Theoretically, N use change in response to Chinese tariff on U.S. agricultural exports is ambiguous. On the one hand, decreased production of soybeans can also lead to a decreased production of corn because these two crops are often planted in rotation. This would decrease N use and runoff. On the other hand, the production of soybeans may be substituted with the production of wheat, which is more N-intensive. As a result, N use and runoff can increase.

Our numerical modeling approach is similar to Marshall et al. (2018), Xu et al. (2022) and Elbakidze et al. (2023). Marshall et al. (2018) use the Regional Environment and Agriculture Programming (REAP) model and data from the USDA Conservation Effects Assessment Project (CEAP) to evaluate land use changes that would achieve a 45% reduction in N runoff to the Gulf. While we rely on a similar economic partial equilibrium representation, our approach differs by modeling county-scale production rather than 273 production regions, which provides a more detailed spatial resolution of agricultural production and land use. We also use the Soil and Water Assessment Tool (SWAT) rather than CEAP to incorporate biophysical production functions and N leaching and transport. Using SWAT, N use in our model is variable at extensive (acreage) and intensive (per acre N use) margins. We extend Xu et al. (2022) by explicitly including endogenous trade, which enables us to

assess the relationships between trade and Gulf N runoff outcomes.

We contribute to the literature with a new spatially explicit integrated assessment model that accounts for economic price feedback, trade, and biophysical dependencies (Kling et al., 2017). Although similar integrated hydro-economic models have been used in prior water-related studies (Jackson et al., 2005; Marshall et al., 2018; Xu et al., 2022), none have been used in conjunction with SWAT to examine the relationship between trade and nutrient runoff from agricultural production to downstream coastal ecosystems. Hence, we provide an innovative modeling infrastructure to help us think about the relationship between agricultural trade, production, and environmental quality. We use the model to a) evaluate the effect of tariffs on U.S. corn and soybeans exports to China on N runoff to the Gulf of Mexico and b) examine the effects of the Gulf of Mexico N runoff restriction objectives on U.S. agricultural exports to China. The empirical model includes spatially explicit county-scale land and N use, enabling the disaggregation of the trade policies' impacts on county-specific land use, fertilizer use, and N runoff.

2. Methods and data

We use a spatial price endogenous partial equilibrium land use model for major crop commodities produced in the U.S. to empirically examine the relationships between environmental outcomes, environmental regulation, and U.S.-China agricultural trade tariffs. Partial equilibrium models (Samuelson, 1952; Takayama and Judge, 1971; McCarl and Spreen, 1980) have been widely used to study policy impacts on consumption, production, and trade of agricultural commodities (Boyd and Krutilla, 1987; Bouamra-Mechemache et al., 2002; Burke and Myeres, 2014). In our setting, output prices are determined endogenously, while prices of inputs are fixed. The effect of input price endogeneity can be investigated in future extensions of the model following Claassen and Horan (2001).

We extend the Integrated Hydro-Economic Agricultural Land use (IHEAL) model by adding international trade among the U.S., China and the rest of the world (ROW) (Xu et al., 2022). The core of the IHEAL model is an economic price endogenous partial equilibrium model (McCarl and Schneider, 2001; Chen et al., 2014; Yi et al., 2018) integrated with SWAT ecohydrological model (Arnold et al., 1998, 2012; Williams et al., 2008),

which is executed within the Hydrologic and Water Quality System (HAWQS) platform (Yen et al., 2016; HAWQS, 2020) to quantify crop yield and N runoff as functions of N use. The IHEAL model includes county-scale production decisions for crop planting, fertilizer use and irrigation. IHEAL can be used to assess production activities and corresponding environmental outcomes for various scenarios. Appendix A presents a detailed description of the IHEAL model, including trade with China and ROW.

The model includes production and N runoff parameters obtained from the SWAT model. Yields are expressed as a function of per acre N use. The model endogenously determines market clearing solutions for the consumption and supply of corn, soybeans, wheat, and sorghum in the U.S., China, and ROW. The U.S. supply is spatially disaggregated to obtain N runoff. We extend the IHEAL model in Xu et al. (2022) by adding trade components, which enables quantifying the effects of trade policies on land use in the U.S. and corresponding N delivery to the Gulf of Mexico. Appendix figure A1 provides the model schematic.

Corn, soybeans, wheat and sorghum are included in the model because these crops are major U.S. agricultural commodities for international trade and are most relevant for fertilizer use assessment (Marshall et al., 2015). The data include production and consumption quantities, prices, and supply and demand elasticities for the U.S., China and ROW. We use production, consumption and price data from 2014 as the baseline to avoid the influence of trade conflicts. Production and consumption data are obtained from USDA FAS (USDA FAS, 2021c). Regional crop prices are from USDA NASS for the U.S., Yi et al. (2018) for China, and FAOSTAT for ROW (USDA NASS, 2021b; FAO, 2021). Transportation costs are 20% of the commodity price in the destination market (Havlik et al., 2011).

Demand and supply elasticities are obtained from several sources. For the U.S., the demand elasticities for corn, soybeans, wheat and sorghum are -0.28, -0.29, -0.34 and -0.3, respectively (Westcott and Hoffman, 1999; Piggott and Wohlgenant, 2002; Ishida and Jaime, 2015). The demand and supply elasticities for China are -0.044 and 0.129 for corn, -0.509 and 0.12 for soybeans, -0.244 and 0.039 for wheat, and -0.36 and 0.112 for sorghum (Zhuang and Abbott, 2007; Chen et al., 2012; Roberts and Schlenker, 2013; USDA ERS, 2014; Koizumi, 2015; Haile et al., 2016). Since there are no available demand and supply elasticities for ROW, we calibrate these data based on values obtained from the literature (Sarris and Freebairn, 1983; Karp and McCalla, 1983; Roberts and

Schlenker, 2013). The calibration procedure is based on reproducing the consumption and production of ROW as close to the observed values as possible by adjusting the ROW demand and supply elasticities in the neighborhood of estimates from the literature. The calibrated ROW demand and supply elasticities are -0.15 and 0.07 for corn, -0.34 and 0.19 for soybeans, -0.045 and 0.05 for wheat, and -0.49 and 0.112 for sorghum, respectively.

U.S. county-specific crop acreages of corn, soybeans, wheat and sorghum from 2005 to 2019 are obtained from the National Agricultural Statistics Service (NASS) (USDA NASS, 2021). Farm resource region-scale crop production costs are obtained from USDA ERS and are converted to county costs based on region and county matching (ERS, 2020). We obtain county-specific SWAT crop yields and N runoff from HAWQS. N delivery ratios, which show the proportion of N delivered from each county to the Gulf of Mexico, are from White et al. (2014).

3. Results and discussion

3.1 Baseline results

Table 1 shows baseline results for model validation comparing model solutions and corresponding observed values in 2014. Reported model solutions include (i) U.S. land use, crop prices, N use and N runoff to the Gulf of Mexico; (ii) consumption and production in the U.S., China and ROW; and (iii) net trade volumes.ⁱⁱ These results also serve as a reference point for scenario analysis.

The baseline estimates for land use in the U.S. are 35.4, 37.5, 19.0 and 3.0 million ha for corn, soybeans, wheat and sorghum, respectively. The annual N use producing these crops in the MRB is 8,472,100 metric tons, which accounts for 70% of the total 2014 N use in the U.S. (USDA ERS, 2019). The corresponding cumulative N runoff to the Gulf is 435,670 metric tons.

3.2 Export Tariffs

This section presents the impacts of Chinese tariffs on major crops imported from the U.S. and water quality in the Gulf of Mexico. We investigate three tariff scenarios, including tariffs on soybeans, corn and both crops. We focus on soybeans and corn in this analysis for the following reasons. First, soybeans and corn

are two major crop commodities produced in the U.S. that are exported to China (USDA FAS, 2021b). Second, soybeans are a major agricultural commodity produced in the U.S. and were most affected by the 2018 U.S.-China trade conflict (CRS, 2018). Third, corn is the largest crop produced in the U.S. in terms of both acreage and production (Adjemian et al., 2021; USDA NASS, 2021b). Fourth, corn is the most N-intensive crop produced in the U.S. and is commonly planted in rotation with soybeans, especially within the MRB. Hence, tariffs on U.S. soybeans and corn exports to China can affect trade, production and environmental outcomes in the Gulf of Mexico.

3.2.1 Tariffs on soybeans

We vary the tariffs on U.S. soybeans exports to China from 0% to 30% with a 5% increment and report corresponding IHEAL solutions in table 2 (panel a). With increased tariffs, U.S. soybeans exports decrease monotonically. Results indicate that the 25% Chinese tariff on U.S. soybeans reduces total U.S. soybeans exports from 59,722 to 51,510 thousand metric tons, a 13.8% reduction relative to the baseline (panel a, Table 2).

The impacts of the U.S. soybeans export tariff on N use in the MRB, the corresponding runoff to the Gulf of Mexico, and crop production in the MRB are presented in Figure 1. Chinese tariff on U.S. soybeans leads to a monotonic increase of N use in the MRB as the production of corn in MRB increases. The decrease in soybeans profitability improves the relative profitability of corn, sorghum, and wheat. As a result, the production of these crops expands relative to lower soybeans tariffs. Fertilizer use in MRB increases because soybeans acreage is replaced with corn, sorghum and wheat, which are more N-intensive. A 25% increase in the tariff on U.S. soybeans exports to China leads to a 1.2% increase in N use and a 0.5% increase in N loading in the Gulf of Mexico. N use increases monotonically, while N delivery to the Gulf does not. In particular, N use increases with higher soybeans tariffs from 0 to 25% but decreases in the 30% tariff scenario relative to the 25% scenario. The reason for the decrease in N delivery is that in the 30% scenario N-intensive crop production moves to lands that require greater N use but have lower delivery ratios and thus have lower N runoff potential to the Gulf.

3.2.2 Tariffs on corn

Next, we examine the effects of corn export tariffs on N runoff to the Gulf. The results of incrementally

increasing the tariff from 0% to 30% (panel b, table 2) show that U.S. corn exports decrease as tariff increases. A 25% Chinese tariff on U.S. corn reduces total U.S. corn exports by 10.1%. Figure 2 presents the results for N use within the MRB, the corresponding runoff to the Gulf, and crop production in the MRB at various tariffs on U.S. corn exports to China. N use within the MRB and N delivery to the Gulf decrease monotonically in response to the increase in corn tariff because corn production decreases. Since soybeans, wheat, and sorghum are less N-intensive than corn, the increase in the acreage of these crops reduces N use and runoff to the Gulf of Mexico. In 2014, the share of corn in agricultural commodity exports from the U.S. to China was 0.3% in terms of market value (United Nations Statistical Division, 2021; USDA FAS, 2021a). Hence, the Chinese tariff on U.S. corn has a small impact on N runoff to the Gulf of Mexico. A 30% increase in the tariff on U.S. corn exports to China reduces corn acreage and production by 0.7% and 0.6%, respectively. As a result, N use within the MRB and delivery to the Gulf decline by 0.6% and 0.4%, respectively (figure 2).

3.2.3 Tariffs on both corn and soybeans

Changes in U.S. corn and soybeans exports in response to the proportional percent increase in tariffs on both commodities are presented in panel c of table 2. Similar to the individual tariffs on soybeans or corn, exports of U.S. soybeans and corn decline with the increase in tariffs imposed by China.

Figure 3 presents the results for N use within the MRB, the corresponding runoff to the Gulf of Mexico, and crop production in the MRB. The changes are similar to the soybeans tariff case because soybeans is the dominant agricultural commodity exported from the U.S. to China (United Nations Statistical Division, 2021). As a result, demand for U.S. soybeans decreases more significantly than corn. The dominant effect of the soybeans tariff on N runoff is consistent with the results of Yao et al. (2021).

The N use within the MRB increases monotonically as tariff increases (Figure 3). In the MRB, soybeans production declines while the production of the other three commodities increases. Although corn is also subject to the tariff and exports decrease, corn production in the MRB increases as acreage previously allocated to soybeans is redistributed to other crops, including corn. Production of wheat and sorghum also increases as soybeans production declines. Corn, wheat and sorghum are more N-intensive commodities than soybeans. Therefore, N use in the MRB increases, as does the N runoff to the Gulf.

3.2.4 Spatial N use and runoff response to U.S.-China trade policies

The previous sections show that Chinese tariffs on U.S. corn and soybeans reduce soybeans production and increase the production of other, more fertilizer-intensive crops within the MRB. This change in production results in greater N runoff and further water quality degradation in the Gulf of Mexico. Heterogeneities of counties within the MRB in terms of economic and environmental factors imply different degrees of susceptibility to a production change in response to trade policies. In this section, we present spatially explicit results for changes in N use and N runoff to the Gulf in response to the 25% soybeans tariff. The results identify locations that are most susceptible to changes in N use and N delivery in response to structural changes in export markets. Counties can differ in terms of productivity with respect to N use and in terms of N transport to the Gulf. Therefore, the locations with the greatest changes in N use do not necessarily produce the biggest changes in N loadings to the Gulf. County-scale N use changes are important due to the implications for local water quality. On the other hand, county scale heterogeneities in N delivery to the Gulf are important for understanding the sources of N loadings in the Gulf. We focus on soybeans because they are the largest U.S. export commodity to China, and the tariff on soybeans accounts for most of the impact on N runoff to the Gulf.

Spatially explicit results for changes in N use and the corresponding N runoff to the Gulf of Mexico relative to the baseline in response to the 25% tariff on U.S. soybeans exports to China are presented in figure 4. The figure shows that N use increases mainly in Illinois, Iowa, Minnesota, Wisconsin, and South and North Dakota counties. These are major soybeans-producing regions. The decreased profitability of soybeans moves planted acreage from soybeans to other more N-intensive crops. The largest increase in annual N use occurs in Hand County, SD, from 6,597 to 12,889 metric tons. Soybeans are Hand County's largest crop, accounting for 42% of all cropland (USDA NASS, 2017). Our model predicts that soybeans acreage decreases from 92,340 to 30,780 ha, while the acreage of wheat increases from 3,213 to 67,700 ha.

The results also illustrate spatial heterogeneities in terms of changes in N runoff to the Gulf of Mexico. The increase in N delivery to the Gulf is mostly attributable to Illinois, Iowa and Minnesota. However, the counties with the greatest increase in N use do not necessarily generate the greatest increase in N delivery to

the Gulf because of spatial heterogeneities in N delivery ratios. For example, although N use in Hand County increases by 6,292 metric tons, the corresponding increase in N runoff in the Gulf of Mexico is 5 metric tons per year. On the other hand, the largest increase in N delivery to the Gulf, with 209 metric tons per year, comes from Boone County, IA, where N use increases by 4,012 metric tons per year.

3.3 The effect of N runoff reduction on exports

The 2008 Gulf Hypoxia Action Plan aims to reduce N runoff to the Gulf of Mexico by 45% (US EPA, 2008; Robertson and Saad, 2013). The effects of reducing N runoff to the Gulf on agricultural exports have not been addressed in prior literature. We use the IHEAL model to estimate the impacts of 10%, 20%, 30% and 45% curtailment of crop N runoff to the Gulf of Mexico on U.S. agricultural exports to China. Importantly, this scenario analysis does not attempt to examine the effect of a particular policy aimed at reducing N runoff. Instead, we examine the implications of a “what if” scenario where N runoff to the Gulf is reduced by a certain percentage, following the EPA Hypoxia Action Plan, without considering explicit policy tools that may be used to achieve such an objective.

Figure 5 presents U.S. net crop exports for various N runoff reduction targets. Reducing N runoff to the Gulf of Mexico has the largest effect on corn exports because corn is the most N-intensive commodity produced in the U.S. Soybeans and wheat exports also decline, although more modestly than corn, because these crops are often planted in rotation with corn. A 45% reduction in N runoff to the Gulf results in ceasing corn exports to China. Soybeans and wheat exports decline by 4% and 60%, respectively. On the other hand, sorghum exports to China increase by 11.5%.

The results reveal an increasing rate of decline in net corn, soybeans and wheat exports in response to N runoff reduction objectives. This finding is consistent with Hartmann (1993), who investigated the effects of reducing N use on agricultural trade and economic welfare in Europe. Although corn, soybeans and wheat production and exports decline in response to restricting N loading in the Gulf of Mexico, the U.S. is still a net exporter of all crops.

Net exports of U.S. sorghum decline in the lower N runoff curtailment scenarios but increase in the highest N runoff reduction scenario relative to the baseline. This is due to the substitute relationship between

corn and sorghum. The 45% N runoff curtailment significantly increases corn production costs and reduces corn production, undermining U.S. corn's competitiveness in the international markets. Since sorghum is a substitute for corn as a grain feed and its production requires relatively less N fertilizer than corn, sorghum production increases relative to the baseline to compensate for corn production losses. As a result, U.S. corn prices increase from \$130 to \$135, \$142, \$150, and \$171 per metric with N runoff reduction goals of 0%, 10%, 20%, 30% and 45%, respectively. Sorghum price declines from \$211 (baseline) to \$204 (45% N reduction) per metric ton. Exports of all crops, except sorghum, decline when N runoff is restricted.

The N runoff curtailment implicitly increases the production costs of N-intensive crops in the MRB. Hence, the production of N-intensive crops declines, and acreage of these crops is substituted with less N-intensive crops. Production of N-intensive crops shifts to lands outside the MRB. Within the MRB, a 45% N runoff curtailment results in a 1%, 7.9%, 6.8%, and 8.7% decrease in acreage and a 21.8%, 8.7%, 7.9% and 12.6% decrease in production. Production declines as a result of changes in extensive (acreage) and intensive (per acre fertilizer use) margins. The production of corn, soybeans, wheat and sorghum outside the MRB increases by 17,708,000, 5,641,000, 1,271,000 and 2,528,000 metric tons relative to the baseline, respectively.

4. Discussion and policy implications

This section provides a comparison of our results with observed data, and discusses corresponding policy implications. In the scenario with a 25% Chinese tariff on U.S. soybeans, total U.S. soybeans exports decline by 13.8%.  USDA FAS reported that U.S. soybeans exports declined from 655,725 thousand metric tons in 2017 to 589,579 thousand metric tons in 2019, a 10.1% reduction, in response to the 25% Chinese tariff announced in July 2018 (USDA FAS, 2021c). Similarly, our results show that a 25% Chinese tariff on U.S. corn reduces total corn exports by 10.1%. USDA FAS reported that U.S. corn exports declined from 52,790 thousand metric tons in 2017 to 41,558 thousand metric tons in 2019, a 17.8% reduction in response to the 25% Chinese tariff announced in July 2018 (USDA FAS, 2021c).

Simulated reductions in U.S. soybeans and corn exports in response to a 25% Chinese tariff are lower than observed according to the FAS data. One reason for this difference is that the 2018 Chinese tariffs were imposed on all agricultural commodities (CRS, 2018), while we focus on a subsetⁱⁱⁱ. Also, trade outcomes in this model

correspond to a long-run equilibrium that reflects adjustments in trade with ROW in response to the tariff. In contrast, the observed data reported by the FAS corresponds to a short-run response to newly imposed tariffs. In the long run, exports may not decrease as much as in the short run because, in the long run, international trade arrangements may adjust to the imposed tariffs by redirecting U.S. exports from China to ROW. Another important caveat is that our model does not account for multi-year export-import contracts.

The results in all modeled scenarios (section 3.2.1, 3.2.2 and 3.2.3) indicate that Chinese tariffs on U.S. crops affect agricultural land use in the MRB and the corresponding N runoff to the Gulf of Mexico. However, the impacts are modest, which is consistent with previous studies on agricultural trade and environmental outcomes (Cooper et al., 2003; Kirchner and Schmid, 2013). Cooper et al. (2003) showed that U.S. agricultural production would vary within the bounds of normal seasonal variations even if all agricultural trade distortions were eliminated. Hence, changes in trade policy would have a small impact on the environment, including soil degradation and N loss to watersheds. Kirchner and Schmid (2013) examined the effect of agricultural trade policies in Austria on regional environmental quality, including nitrogen and phosphorus emissions, soil organic content, and irrigation water use. They found that trade policies have statistically significant but small effects on N and P emissions.

Our results show that the effect of agricultural trade barriers on the environmental outcome can depend on the targeted commodity. Tariffs on some crops can improve environmental outcomes, while tariffs on other crops can perpetuate negative environmental externalities. For example, soybeans are the largest exported commodity from the U.S. to China. Fifty-two percent of U.S. soybeans production is exported to China (USDA FAS, 2021a). Therefore, a contraction in the soybeans export market can result in decreased production of soybeans and increased production of other crops, including corn (Reed and Riggins, 1981; Rathmann et al., 2010). Soybeans export tariff can redistribute soybeans acreage to more fertilizer-intensive crops, including corn and wheat. A 25% tariff on soybeans reduces soybeans production in the MRB by approximately 3% and increases corn production by less than 1% (Figures 1). This production adjustment has a positive but small, 0.5%, effect on N runoff to the Gulf of Mexico. When a 25% tariff imposed on both corn and soybeans, soybeans production in the MRB is reduced by 2.5%, and corn production is increased by less than 1%. This

production change leads to a 0.2% increase in N runoff to the Gulf of Mexico. The corn tariff in isolation reduces N loading in the Gulf of Mexico because corn is one of the most fertilizer-intensive crops produced in the U.S. (figure 2). However, the U.S. exports only 2% of its corn production to China. Therefore, a tariff on U.S. corn exports to China results in a small (0.6%) decrease in corn production and a modest 0.3% decrease in N runoff to the Gulf.

In addition to the aggregate results, we also obtain spatial N use and runoff changes in response to U.S.- China trade friction. The county scale results indicate that trade friction has regionally heterogeneous impacts on N use in the MRB and loading to the Gulf. N runoff to the Gulf intensifies from Illinois, Iowa and Minnesota as soybeans acreage is substituted with corn and wheat. This result offers an important insight relative to Yao et al. (2021), who document U.S. regional changes in nutrient surplus as a result of a trade barrier between the U.S. and China but do not account for the downstream implications.

Our results also imply that agricultural trade can affect local environmental quality as a result of changes in N use at the county scale. Chinese tariff on U.S. soybeans decreases soybeans production and increases production of other, more N-intensive crops in several regions. Greater N use in counties with larger shares of soybeans acreage, which are substituted with more N-intensive crops, degrades local water quality. Our results show that water quality in some counties in South Dakota, Minnesota, and Iowa is particularly susceptible to increased N runoff due to Chinese tariff on U.S. soybeans (figure 4). Hence, a policy aimed at improving or protecting regional water quality should account for spatial heterogeneity in the susceptibility to the increase in N runoff in response to trade disruption. Similar spatial targeting of N management policies was implied in previous literature (Rabotyagov et al., 2014).

This study also quantifies the impacts of environmental policies on U.S. exports in section 3.3. Results imply that, to some degree, environmental and trade policies can affect U.S. exports similarly. For example, a 10% N runoff reduction decreases corn production, which results in a 14.5% drop in corn exports to China (figure 5). Similarly, a 25% tariff on corn and soybeans results in a 14.5% decrease in corn exports (table 2). The export of U.S. soybeans declines by 4% when N runoff to the Gulf is reduced by 45% (figure 5), and by 3.5% when the 5% tariff is imposed on corn and soybeans exports to China (table 2).

5. Conclusion

The interdependence between international trade, agricultural production, and nutrient runoff from agricultural production to the Gulf of Mexico has received limited attention in academic literature. International trade frictions affect not only commodity and labor markets but also land use, production, and environmental outcomes. Conversely, environmental policies can affect production activities and international trade outcomes. We use an integrated assessment model with a partial equilibrium commodity market and spatially explicit land use to explore the environmental impacts of U.S.-China trade policies. In particular, we investigate how the Chinese tariff on U.S. agricultural commodity exports affects water quality in the Gulf of Mexico. Results indicate that Chinese tariffs on U.S. agricultural imports have modest impacts on water quality in the Gulf of Mexico and that the impacts depend on which commodities are most affected by the trade barrier.

We also quantify the effects of water quality regulation in the Gulf of Mexico on agricultural trade between the U.S. and China. Reducing agricultural N runoff to the Gulf decreases crop production within the MRB, with some of the lost production relocating to regions outside of the MRB. However, aggregate production declines, resulting in reduced exports. The export contraction can be comparable to the trade adjustment in response to a tariff increase.

The results must be placed within the context of several caveats inherent in our methodology. Since this study focuses on agricultural trade between the U.S. and China, the first caveat concerns the level of aggregation in trade with ROW. The model does not explicitly account for trade flow adjustments between the U.S., China and countries included in ROW. All countries, other than the U.S. and China, are combined in ROW and trade with ROW is expressed in a net form. Nevertheless, while the model is not suitable for analyzing trade flow between individual countries included in ROW, the aggregation is unlikely to affect our estimates of production activities in the MRB and N runoff to the Gulf of Mexico. Second, the model is not suitable for evaluating the short-run impacts of trade policies on N runoff. Instead, the model corresponds to long-run equilibrium outcomes. In this respect, the model a) does not account for multiyear production and import-export contracts, and b) produces equilibrium results that implicitly account for optimal adjustments in interregional trade such

that Chinese imports from the U.S. are replaced with imports from ROW while U.S. exports are redirected from China to ROW. Third, the IHEAL model estimates changes in N runoff only in response to changes in planted acreages and per acre N use. Best management practices are not explicitly included in the model. Fourth, commodity demand is represented at the national scale and does not explicitly account for regional demand heterogeneities in the U.S. Although such aggregate representations of demand are common (Xu et al. 2022; McCarl and Schneider, 2001; Chen et al., 2014), future work decomposing the national U.S. commodity demands into regional demands may be worth pursuing to explicitly investigate the implications of transportation costs within U.S. Fifth, the partial equilibrium model assumes that only the prices of the four modelled commodities are endogenous while the rest of the output and input prices are fixed. An extension of the model can consider the endogeneity of other prices, including land and other inputs.

Grouped Footnotes

ⁱ For a detailed discussion of the 2018 U.S.-China trade conflict and its economic impacts see Grant et al. (2021).

ⁱⁱ We present the net trade volume instead of nominal trade flows because the highly aggregated nature of exports and imports in ROW distorts the prediction of nominal interregional trade flow. Hence, net trade volumes are reported rather than nominal trade flows.

ⁱⁱⁱ We examine tariffs on one crop at a time to illustrate the heterogeneity of relative impacts of tariffs imposed on different crops.

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Table 1. Baseline simulation results and observed 2014 data.

U.S. land use, crop prices, N use and runoff to the Gulf of Mexico						
	Acreage		Price (\$/metric ton)			
	Model	Observed (2014)	Model	Observed (2014)		
Corn (million ha) ^a	35.4	36.7	130	146		
Soybean (million ha) ^a	37.5	33.7	404	371		
Wheat (million ha) ^a	19.0	23.0	201	220		
Sorghum (million ha) ^a	3.0	2.9	211	164		
N applied in the MRB (1,000 metric tons)	8,472	12,098 ^b				
N delivered to the Gulf (metric ton)	435,670	796,000 ^c				
Domestic consumption (1,000 metric tons)						
	The U.S.		China		ROW	
	Model	Observed	Model	Observed	Model	Observed
Corn	324,020	314,519	257,570	255,267	475,150	470,132
Soybean	56,200	57,673	93,240	90,893	176,680	170,606
Wheat	36,760	35,740	129,170	129,358	562,730	560,379
Sorghum	1,883	2,063	13,840	12,653	51,100	51,238
Production (1,000 metric tons)						
	The U.S.		China		ROW	
	Model	Observed	Model	Observed	Model	Observed
Corn	360,120	361,136	252,120	249,764	444,500	446,730
Soybean	115,920	106,905	12,610	12,686	197,590	201,599
Wheat	56,010	55,147	128,260	128,235	544,390	546,938
Sorghum	12,073	10,988	2,430	2,500	52,320	52,286
Net export (+)/import(-) (1,000 metric tons)						
	The U.S.		China		ROW	
	Model	Observed	Model	Observed	Model	Observed
Corn	36,100	46,617	-5,450	-5,503	-30,650	-23,402
Soybean	59,720	49,232	-80,630	-78,207	20,910	30,993
Wheat	19,250	19,407	-910	-1,123	-18,340	-13,441
Sorghum	10,190	8,925	-11,410	-10,153	1,220	1,048

Note: The table provides simulated production, prices, consumption and net exports in the baseline scenario without trade friction.

The table also provides the corresponding observed 2014 data for comparison as part of validation.

^a Observed values for U.S. land use and crop prices were obtained from USDA NASS (USDA NASS, 2021b); observed values for domestic consumption, production and net trade volume came from USDA FAS (USDA FAS, 2021c)

^b Refers to the 2014 N fertilizer consumption in the U.S. Source: USDA ERS, 2019.

^c This number refers to N runoff to the Gulf of Mexico from all cultivated agriculture in the MRB. Source: White et al., 2014

Table 2. Simulated U.S. net crop exports

Panel a: Chinese tariffs on imports of U.S. soybean							
	0%	5%	10%	15%	20%	25%	30%
U.S. net corn exports (1,000 metric tons)	36,100	35,910	35,461	35,487	35,539	34,770	34,950
U.S. net soybean exports (1,000 metric tons)	59,722	57,788	55,871	54,628	53,510	51,510	50,614
U.S. net wheat exports (1,000 metric tons)	19,250	18,980	19,080	19,297	19,290	19,450	19,430
U.S. net sorghum exports (1,000 metric tons)	10,190	12,156	10,308	10,350	10,414	10,609	10,640
Panel b: Chinese tariffs on imports of U.S. corn							
	0%	5%	10%	15%	20%	25%	30%
U.S. net corn exports (1,000 metric tons)	36,100	35,320	34,720	34,020	33,210	32,464	32,170
U.S. net soybean exports (1,000 metric tons)	59,722	59,749	59,730	59,710	59,715	59,770	59,740
U.S. net wheat exports (1,000 metric tons)	19,250	19,210	19,170	19,140	19,110	19,080	19,079
U.S. net sorghum exports (1,000 metric tons)	10,190	10,190	12,087	12,124	10,239	10,239	10,237
Panel c: Chinese tariffs on imports of U.S. soybean and corn							
	0%	5%	10%	15%	20%	25%	30%
U.S. net corn exports (1,000 metric tons)	36,100	34,780	33,910	33,280	32,010	31,590	31,190
U.S. net soybean exports (1,000 metric tons)	59,722	57,651	55,910	54,645	53,100	51,610	50,752
U.S. net wheat exports (1,000 metric tons)	19,250	18,991	19,096	19,260	19,360	19,490	19,430
U.S. net sorghum exports (1,000 metric tons)	10,190	10,266	10,313	10,382	10,531	12,490	10,641

Note: This table presents the simulated results for the U.S. net crop exports in various tariff scenarios. The tariffs are increased from 0 to 30% in 5% increments.

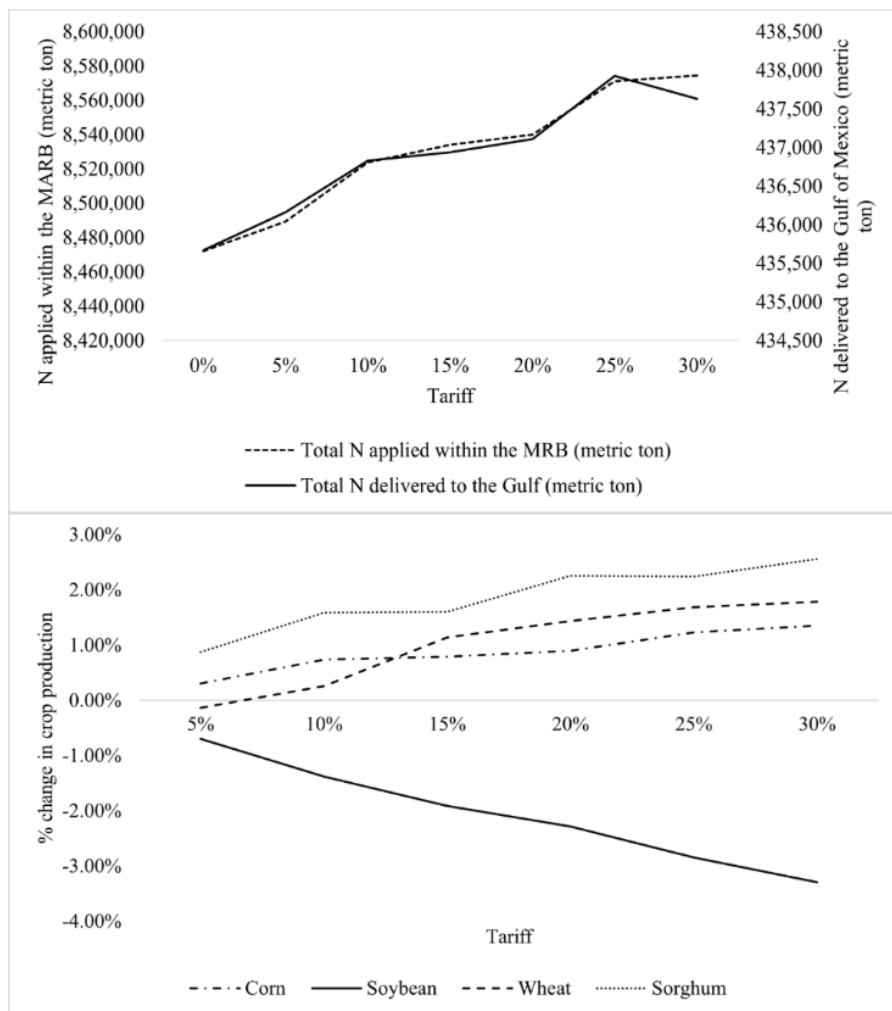


Figure 1. N runoff and crop production in the MRB with Chinese tariffs on soybean

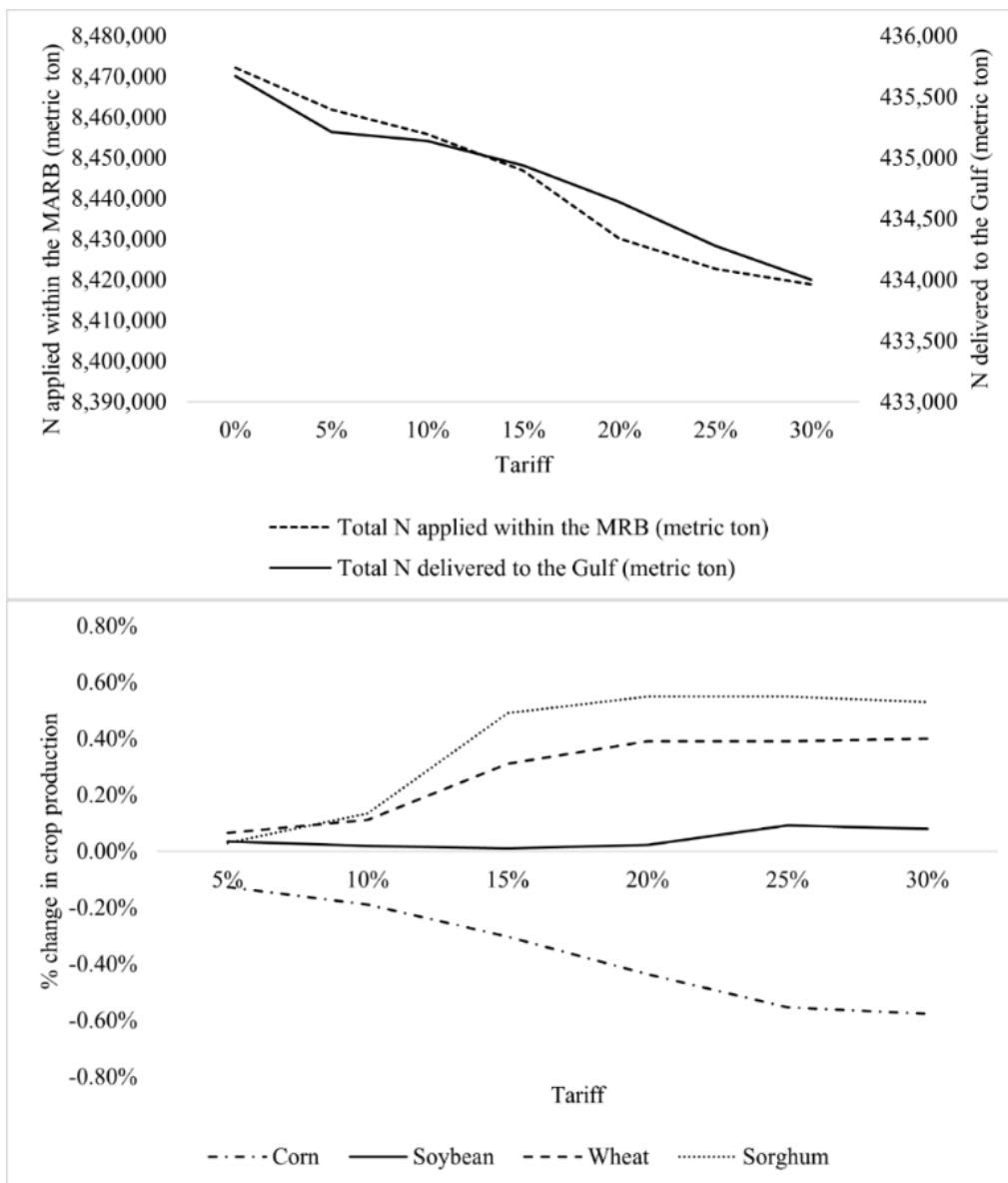


Figure 2. N runoff and crop production in the MRB with Chinese tariffs on corn

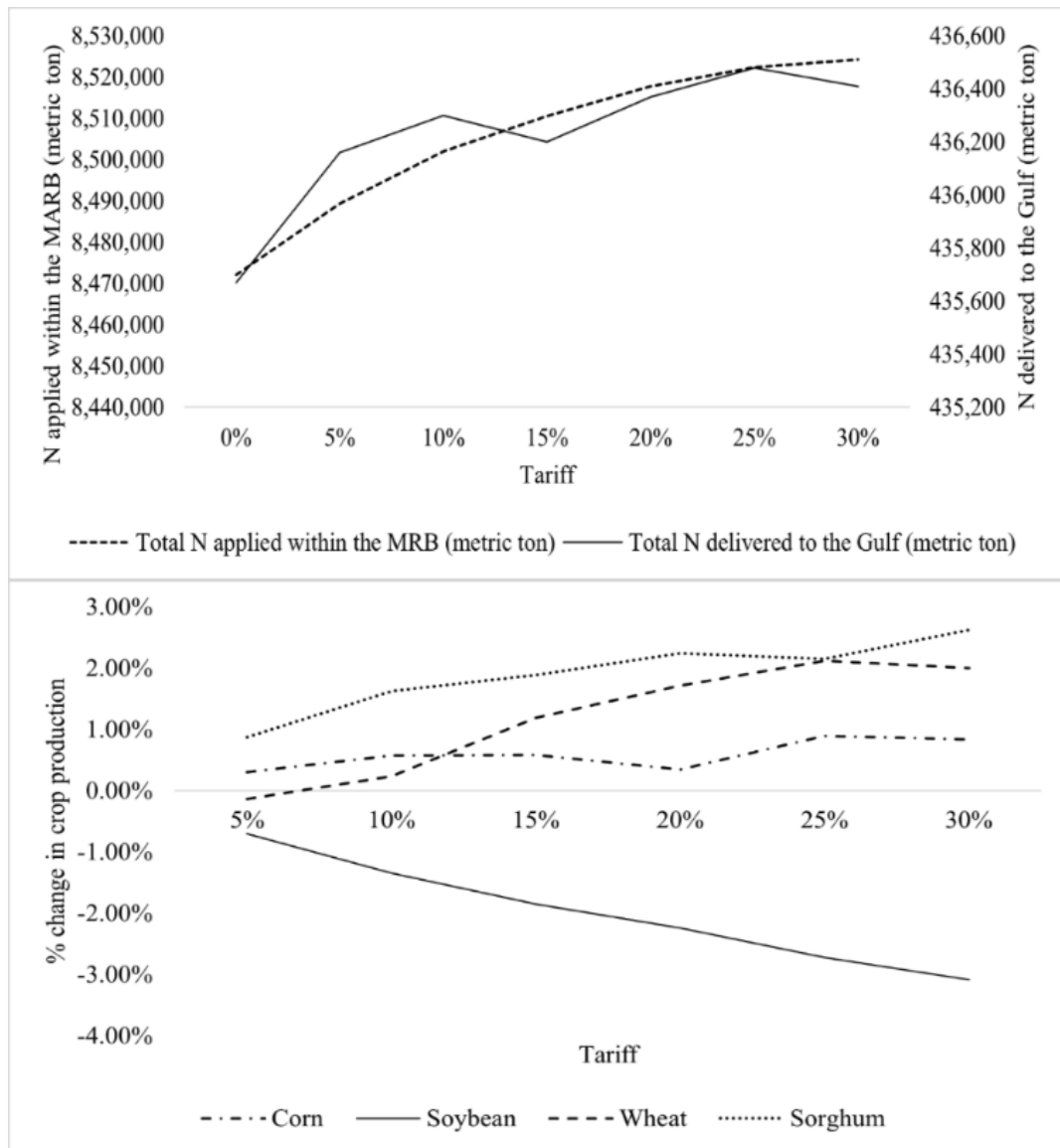


Figure 3. N runoff and crop production in the MRB with Chinese tariffs on soybean and corn

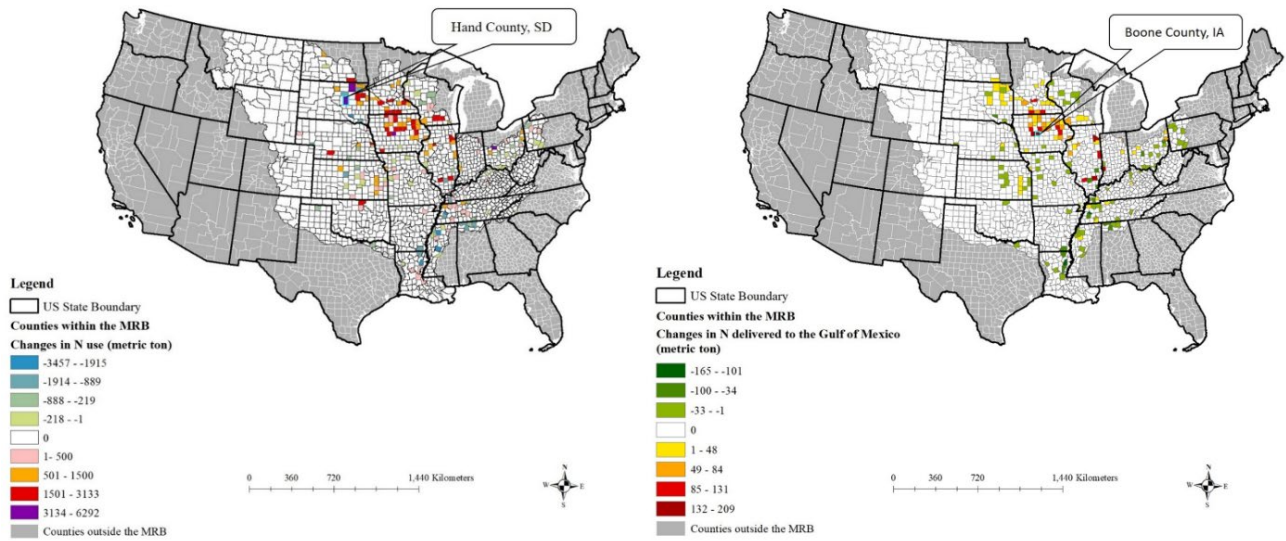


Figure 4. Changes in N use (left panel) and the corresponding N delivery (right panel) to the Gulf of Mexico with a 25% tariff Chinese tariff on U.S. soybean

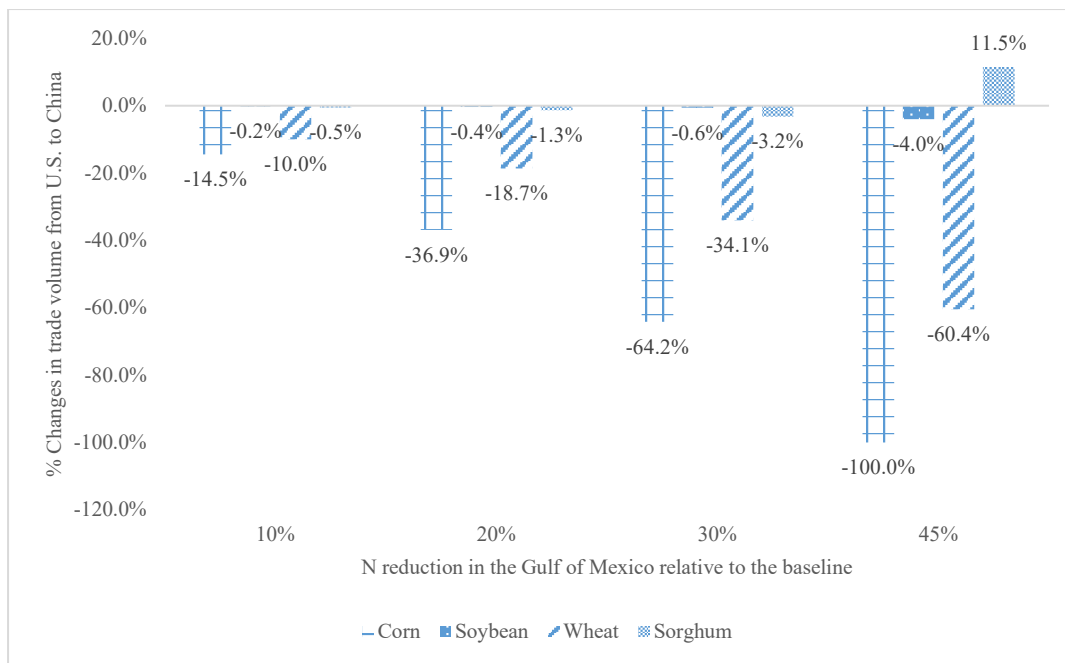


Figure 5. U.S. net crop export changes in response to reducing N runoff to the Gulf of Mexico

Appendix A. IHEAL model

Following prior literature (Havlík et al. 2011; Xu et al 2022), consumer and producer surplus in the US, China and ROW is expressed as follows in equation B1. The objective function maximizes the net benefits as a difference between consumer benefits (area under demand curve) and total cost in c crop markets.

$$\max_{X,L} \sum_c \left[\int_0^{X_c^d} P_c^d(X_c^d, \omega_c) dX_c^d - \sum_{c,i,n,w} tc_{ci} * L_{cinw} - \sum_{c,i} FC_{ci} - \sum_{c,i} WC_{ci} + \sum_{k=China,ROW} \left(\int_0^{X_{kc}^d} P_{kc}^d(X_{kc}^d, \omega_{kc}) dX_{kc}^d - \int_0^{X_{kc}^s} P_{kc}^s(X_{kc}^s, \omega_{kc}) dX_{kc}^s \right) \right] \quad (B1)$$

The first line of the objective function expresses US net benefits as a difference between consumption benefits and production costs, which depend on planted acreages and input uses (acreage, N and water use). This representation of total costs, as opposed to the area under the supply curve, is a suitable approach to express total costs as a function of input use rather than out quantity (Havlík et al. 2011; Xu et al 2022). The second line provides consumer and producer surplus in China and ROW. For these regions, land and production input uses are not explicitly modeled because the objective of this study does not include impacts on production decisions and environmental impacts outside of the US. Therefore, total costs in these regions are modeled as functions of output quantity using areas under the supply curves.

X_c^d is consumption of crop c in the US. X_{kc}^d and X_{kc}^s are consumption and supply of crop c in region k, where k is China or ROW. tc_{ci} is per ha production cost excluding N fertilizer and water use for crop c in county i. L_{cinw} is the acreage of crop c in county i with n kg N fertilizer application and w water use. FC_{ci} and WC_{ci} are total N fertilizer and water costs for crop c in county i, respectively. The objective function is subject to the following constraints:

$$\sum_{n,w} y_{cinw} * L_{cinw} \geq X_{ci}^s \quad \forall c, i, \quad (B2)$$

$$FC_{ci} = \sum_{n,w} \theta_{cin} * L_{cinw} \quad \forall c, i, \quad (B3)$$

$$WC_{ci} = \sum_{n,w} \mu_{ciw} * L_{cinw} \quad \forall c, i, \quad (B4)$$

$$X_c^d \leq \sum_i X_{ci}^s + \sum_{k=China, ROW} I_{c,k} - \sum_{k=China, ROW} E_{c,k} \quad \forall c, \quad (B5)$$

$$X_{kc}^d \leq X_{kc}^s - I_{c,k} + E_{c,k} + NTCROW_{ckk}, \quad \forall c, k \quad (B6)$$

$$\sum_{n,w} L_{cinw} = \sum_m \tau_{mi} * h_{cim} + \sum_n \gamma_{vi} * s_{civ} \quad \forall c, i, \quad (B7)$$

$$\sum_m \tau_{mi} + \sum_n \gamma_{vi} = 1 \quad \forall i. \quad (B8)$$

Equation (B2) constrains aggregate supply of crop c to be no greater than the total production, which is expressed as a sum of per ha yield times corresponding number of hectares. Per ha yields, y_{cinw} , are expressed for each crop c in county i , using fertilizer quantity n and water quantity w . These yield relationships are obtained from the process-based physical model discussed in section 3. Equation (B3) computes total fertilizer costs for crop c in county i , using θ_{cin} as the per ha cost of applying n quantity of fertilizer for crop i in county c and number of hectares, L_{cinw} , of crop i planted in county c using fertilizer and water quantities n and w . Similarly, equation (B4) computes total water costs, using μ_{ciw} as the per ha cost of using w amount of water for crop c in county i .

Equations (B5) and (B6) provide supply and demand balance conditions in the US, China and ROW. (B5) is the balance condition for US, where $I_{c,k}$ and $E_{c,k}$ are US imports and exports from and to China and ROW respectively. (B6) balances local demand and supply, US imports and exports, and net trade of crop c between China and ROW ($NTCROW_{ckk}$).

Equations (B7) and (B8) restrict land allocation to crop c in county i . The constraint represents a convex combination of historical and synthetic acreages, which allows for flexibility in planted crop acreage decisions for each crop between the lower and upper bounds of crop mixes. This formulation implicitly reflects technological, managerial and policy factors restricting crop planting decisions (McCarl, 1982; Schneider et al., 2007; Elbakidze et al., 2012). Following Chen and Önal (2012), we use historical and synthetic crop mix specifications for greater model flexibility.

Synthetic acreages are obtained assuming that a crop acreage response is a function of a vector of crop

prices and lagged acreages of competitor crops (Chen and Onal, 2012). Own and cross acreage-price elasticities, elasticities of own and cross-lagged acreages, and hypothetical price scenarios are used to generate synthetic acreages. To obtain the own and cross acreage-price elasticities and elasticities of own and cross-lagged acreages, we use county production and price data from 2005 to 2019 and the log-log specification of the fixed-effect Arellano-Bond estimator:

$$Acreage_{cit} = \beta_0 + \beta_1 Acreage_{c,i,t-1} + \beta_2 Acreage_{-c,i,t-1} + \beta_3 Price_{c,i,t-1} + \beta_4 Price_{-c,i,t-1} + Climate_{i,t} + TimeTrend_t + \mu_i + \varepsilon_{it} \quad (B9).$$

The use of synthetic representation allows for greater model flexibility, which is useful in circumstances that have not been observed previously, including price or environmental regulation scenarios. In equation (B7), county acreage of crop c is a convex combination of historical and synthetic crop mix acreages. The indexes m and v are historical and synthetic crop mixes; H_{cim} and S_{civ} are m -th and v -th county-specific historical and synthetic crop acreages, respectively; τ_{mi} and γ_{vi} are endogenously determined weights which sum to 1 in equation B8.

County-scale N delivery ratios are used to estimate N runoff to the Gulf of Mexico. We obtain weighted average N delivery ratios according to HUC8 land area in each county. The SWAT HUC 8 sub-basin N delivery ratios are from White et al. (2014). N delivery to the Gulf of Mexico is computed as follows:

$$TN = \sum_i^I \left(dr_i * \sum_{c,n,w} nrf_{cinw} * L_{cinw} \right) \quad (B10)$$

where, TN is N runoff to the Gulf; dr_i is the N delivery ratio for county i ; nrf_{cinw} is the per-ha N runoff from planting crop c with fertilizer use n and irrigation w in county i . Only the counties in the MRB are used in the estimation of N runoff impacts. Figure B1 presents the schematic flow of the IHEAL.

Data

County-specific historical crop acreage and corn, soybean, wheat and sorghum prices from 2005 to 2019 are obtained from NASS (USDA NASS, 2021). We only included observations from the recent 15 years to avoid including land that may no longer be available for planting. County-scale wheat acreages are not available

in NASS after 2008. Therefore, we use CropScape data to fill in missing values (USDA NASS Cropland Data Layer, 2020). Crop production costs, excluding energy, fertilizer and water in 2018, are obtained from USDA ERS. These data are available at the farm resource region scale and are converted to the county scale through region-county matching provided by USDA ERS (ERS, 2020).

Fertilizer and water costs are modeled differently for counties within and outside the MRB. Per ha fertilizer application, water use and yields in the counties outside of the MRB are fixed, with the data obtained from USDA (ERS, 2020; USDA NASS, 2021). Yields within the MRB are expressed as a function of N use and irrigation. Hence, within the MRB, these costs vary depending on N use and irrigation. The fertilizer cost is \$1.32 per kg N element, estimated based on the cost of 30% N solution and N fertilizer price index obtained from USDA ERS (USDA ERS, 2019). The per-ha cost of full irrigation is the cost of purchased irrigation water obtained from ERS (ERS, 2020). Water costs for deficit irrigation are proportionally approximated using the costs of full irrigation. For example, if the water purchased for full irrigation is \$1 per ha, then 75% deficit irrigation will cost \$0.75 per ha.

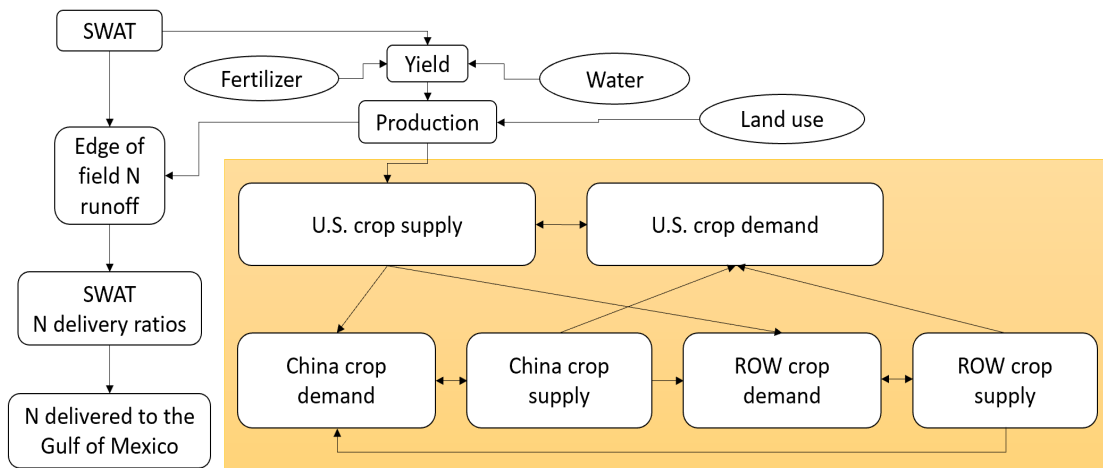


Figure A1. The IHEAL model