Animal Disease Outbreaks and Upstream Soybean Trade

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Abstract

Animal disease outbreaks have been extremely disruptive to global livestock industries in recent years. In light of the modern integration of international supply chains, to what extent have these disruptions been experienced by upstream stakeholders? This research investigates the upstream impacts of global animal disease outbreaks in the international soybean market. We employ a two-step procedure to deduce the impacts of animal disease on upstream soybean trade. We first use a standard, econometric gravity model to empirically estimate the relationship between observed trade and livestock production patterns (accounting for each country's economic masses and trade frictions). We then conduct a counterfactual analysis with our estimated gravity relationships to assess the value of lost soybean trade using a global repository of disease-specific animal mortality data. Our results indicate that between 2005–2020, animal disease outbreaks have cost the international soybean market approximately $5 billion in lost trade. The average exporter loses as much as 2% of its export potential each year. These losses are primarily attributable to cattle disease outbreaks in East Asia and South America. Foot-and-mouth disease alone has cost the soybean trade market approximately $4 billion in lost trade over our sample period.

Keywords: Soybean trade, Animal diseases, Livestock production

JEL Codes: Q17 (Agriculture in International trade), Q18 (Agricultural policy)

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1 Introduction

Animal disease outbreaks have been extremely disruptive to global livestock industries over time and can have far-reaching impacts upstream and downstream. The African swine fever (ASF) outbreak in China caused decreased swine production and increased pork prices, leading to 1% to 2% decline in the national GDP (You et al., 2021). It also created opportunities for higher pork exports globally to meet domestic demand, raising global pork prices by 17% to 85% and increasing demand for alternative animal proteins like poultry and beef (Mason-D'Croz et al., 2020). Major protein exporters have the added complexity of trade bans. For example, the United States experienced a large-scale outbreak of highly pathogenic avian influenza (HPAI) between December 2014 and June 2015. This HPAI outbreak resulted in the death or destruction of more than 50 million chickens and turkeys in the U.S., which was 12% of the table-egg laying population and 8% of turkeys grown for meat (Ramos et al., 2017). The outbreak was one of the most expansive in U.S. history. It required $879 million in public expenditures for disease eradication (Seeger et al., 2021), resulted in an estimated economy-wide direct cost of $3.3 billion (Johansson, Preston and Seitzinger, 2016), and led to the highest table egg prices in more than 30 years (Huang, Hagerman and Bessler, 2016).

Globally, one of the most economically damaging diseases is foot-and-mouth disease. Multiple countries have experienced significant economic losses associated with FMD, particularly in high-profile European and Latin American outbreaks in the year 2001. FMD outbreaks across previously FMD-free countries and zones have been estimated to create annual losses in excess of $1.5 billion per year (Knight-Jones and Rushton, 2013). The 2001 United Kingdom FMD outbreak resulted in substantial livestock death and cost, with estimates of domestic cost between $12.3 billion and $13.8 billion (Scudamore and Harris, 2002). Response policy played a large role in these losses (Grau et al., 2015; Grubman and Baxt, 2004), with UK animal health authorities changing the aggressiveness of their response policy a few years later in a 2008 FMD outbreak. In the last 20 years, the global livestock industry has continued to evolve, shifting trade flows, trade agreements with sanitary policies, and consequently vulnerabilities to FMD outbreaks. Losses in Latin America from the 2001 series of FMD outbreaks in five countries were estimated to range from $439,900 in Columbia to $68 million in Brazil (Countryman and Hagerman, 2017). Similar size FMD outbreaks in Brazil under current export levels could potentially cost $132 million to $271 million, depending on the severity of trade restrictions simulated (Menezes, 2022). Each of these outbreaks had different production systems, different trade relationships, and different market dynamics.

Highly contagious transboundary animal diseases (TADs) that cause disruptions in domestic supply chains, such as these, have consequences upstream as well. However, the upstream costs, if reported, are typically only examined in the context of calculating a national producer welfare loss due to the disease. Rarely are upstream damages examined in any depth, but they can be quite significant. In the Johansson, Preston and Seitzinger (2016) examination of the 2014-2015 HPAI outbreak, crop sector losses due to feed demand reduction made up 52% of estimated producer welfare losses. Feed input price declines in China during ASF were similar in size to the increases in meat substitutes, with soybean meal prices declining by an estimated 5% (Mason-D'Croz et al., 2020). These studies only examine feed grain price changes in the disease-affected country, but reductions in global feed grain demand impact all feed grain exporting countries. In light of the modern integration of international supply chains, to what extent have upstream stakeholders experienced these disruptions?

This research investigates the upstream impacts of global animal disease outbreaks in the international soybean market. Feed grains used for livestock can vary over time. However, soybeans represent a substantial share of the global trade of agricultural commodities and constitute the primary source of amino acids in animal feed. Soybeans are "crushed" separating the soybean oil from the soybean meal, then marketed for separate uses. The soybean meal is primarily used for animal feed globally, with over 95% of global soybean meal production destined for animal feeding (about 76% of total crush by weight) (Economic Research Service, 2024). Soybean meal is a high-quality, plant-derived protein source for animal diets, including swine, poultry, and cattle (Sudarić, 2020).

Given the predominance of soybean meal in animal diets globally and the importance of animal feeding for soybean trade, the international soybean market is the ideal context in which to analyze the effects of animal disease outbreaks on upstream feed trade. This study will focus on animal disease disruptions to global soybean trade. Our analysis expands on previous studies to look beyond case studies on specific outbreaks to examine and compare the effects of a host of diseases across the three primary livestock industries—cattle, swine, and poultry.

We employ a two-step statistical procedure to analyze the impacts of global animal disease outbreaks on upstream trade. We first use a standard, econometric gravity model to empirically estimate the relationship between observed trade and livestock production patterns (accounting for each country's economic masses and trade frictions). We then conduct a counterfactual analysis with our estimated gravity relationships to assess the value of lost soybean trade using a global repository of disease-specific animal mortality data. The logic for our two-step empirical approach is as follows: To the extent that these countries depend on soybean imports to feed their domestic livestock populations, we expect a positive relationship between the value of soybean imports and livestock populations. If an animal disease outbreak reduces the number of livestock animals in the importing country, we anticipate stakeholders to respond by importing less soybeans. An improved understanding of this indirect impact related to upstream industries is crucial to provide information on the full costs and benefits of disease outbreaks, as well as prevention and control strategies.

Our results suggest that between 2005 and 2020, animal disease outbreaks have cost the international soybean market approximately \$5 billion in lost trade. The average soybean exporter loses as much as 2% of its export potential each year. These losses are primarily attributable to cattle disease outbreaks in East Asia and South America. Foot-and-mouth disease alone has cost the soybean trade market approximately \$4 billion in lost trade over our sample period.

The remainder of this manuscript is organized as follows. A more complete review of the literature on the varied economic pressures of TADs is presented in Section 2. Section 3 describes the data we use for the analysis. Section 4 outlines the two-step procedure we employ to deduce the impacts of animal disease on upstream soybean trade. Section 5 presents our results, and Section 6 considers a number of robustness checks to gauge the reliability and sensitivity of our estimates. Finally, Section 7 concludes with a discussion of implications for policymakers and briefly offers some caveats to our findings.

2 Literature Review

From an economic theory perspective, the occurrence of a high-consequence TAD outbreak represents a negative production shock (or, equivalently, an increase in the marginal costs of production) for the affected livestock production sector. Unlike endemic animal diseases—those already circulating in a country—TADs like ASF, HPAI, and FMD create a negative externality in the supply chain. In the immediate run, affected livestock producers suffer economic losses due to animal deaths and increased production costs related to mitigation and control. Some countries have animal health policies in place that help offset the farm gate losses for livestock producers. This includes indemnity or payments for livestock depopulated in disease control efforts. These policies vary by country but are generally limited to producers directly impacted by disease. As a result, producers of upstream goods like feed or producers adversely affected by price changes should have business continuity plans in place (Thompson et al., 2019).

A large body of research has analyzed the direct effects of animal disease outbreaks on livestock markets and trade (de Menezes, Ferreira Filho and Countryman, 2023; MacLachlan, Boussios and Hagerman, 2022; Schaefer, Scheitrum and van Winden, 2022; Scheitrum, Schaefer and van Winden, 2023; Seeger et al., 2021). Less focused work has examined indirect impact pathways. Most importantly for our purposes, the direct effects of animal disease on livestock producers have indirect consequences for related, upstream industries. Animal mortality and increased production costs for livestock producers lead to a decrease in the demand for animal feed, and the effects are large enough to reduce prices and economic returns for raw material suppliers in the market for feed grains. This is more apparent in species and countries with intensive grain-based finishings, as opposed to extensive pasture-based finishing. Due to the duration of animal production cycles, the negative consequences of animal disease can be long-lived for some species. It is relatively faster to repopulate poultry inventory, for example, than beef or dairy cattle inventory. However, even in short-cycle poultry, biological lags play an important role in market recovery (Mitchell, Thompson and Malone, 2023). Inventory recovery under biological lags consequently affects the speed of recovery in feed grain markets.

Improved understanding of feed grain price changes is important for the overall effect of the disease on consumers and producers not directly affected by disease on their farm. Increases in farm-gate costs mean consumers pay higher prices for animal-sourced foods in outbreaks that are large enough to more than offset trade bans, as was the case in the Chinese ASF outbreak. Alternatively, if the primary export is exempt from trade bans due to pasteurization or processing, consumer prices may increase. Such was the case with table egg prices in the U.S. in 2014-2015 and in 2022-2023, in which egg prices rose sharply because the supply shock was larger than the decline in fresh and hatching egg export volume (Ramos et al., 2017).

However, for large net exporting countries, a small outbreak can reduce domestic livestock and meat prices. In this case, a decline in the price of feed grains provides some reprieve from input price pressure for remaining livestock producers. Policies to offset damage experienced by producers not directly affected by disease do not generally exist. Large farm gate price declines were seen in the 2022 Brazilian bovine spongiform encephalopathy (BSE) outbreak and the 2003 U.S. BSE outbreak. In addition, consumers may exhibit avoidance behaviors particularly for diseases that have zoonotic potential. This can exacerbate farm gate price declines. [1]

For net livestock and animal product exporting countries, shocks to domestic markets can be dampened through regionalization—agreements to limit the geographic extent of trade bans in combination with extensive disease surveillance, allowing trade from non-infected regions to continue unimpeded. The 2014-2015 US HPAI outbreak resulted in a mix of trade ban levels, from national bans to bans restricted to affected countries or control zones (Seitzinger and Paarlberg, 2016; Thompson, 2018; Thompson et al., 2020). Regionalization is increasingly becoming the standard for bilateral trade bans. As a result, this affects the extent of disease spread and impacts pre-outbreak trade partnerships on a global scale.

Lost global market share can be difficult to recover for a country impacted by a TAD, as importing countries will find new partnerships. Taha and Hahn (2014), for example, found that the 2003 BSE outbreak in the U.S. caused an immediate decline in total U.S. beef exports for several trade partners, despite BSE discovery being restricted to a single animal. Trade bans were lifted over time, but the economic recovery period from this outbreak lasted more than 10 years, (Carriquiry et al., 2019). In contrast, the U.S. poultry industry proved to be more resilient to short-term economic shocks caused by animal disease in 2008 and 2014-2015 (MacLachlan, Boussios and Hagerman, 2022). However, the longer 2022-2023 HPAI outbreak has resulted in continued imposition and release of trade bans under regionalization (Padilla and MacLachlan, 2023).

Literature on direct consequences of disease is rich, and some of these studies also include crop sector impacts, particularly those using partial equilibrium modeling. However, crop losses are rarely reported independently; instead, they are often aggregated into the total loss of producer welfare. FMD outbreaks in two states of the U.S. were compared and welfare losses ranged from \$2.7 billion to \$21.9 billion (Hagerman et al., 2012), and even

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[1] Existing research suggests emergence of a zoonotic or non-zoonotic animal disease outbreak can result in a reduction in the demand for related animal-sourced foods if consumers are worried about the potential for human illness (whether or not this concern is justified).

at a smaller regional level FMD is expected to be very costly with Pendell et al. (2007) estimating $1 billion loss in a 14 county region of Kansas. These studies involve case studies of specific outbreaks in individual regions. Johnson and Pendell (2017) use a numerical model to analyze the impacts of reducing bovine respiratory disease (BRD) prevalence among the U.S. feedlots to feed and grain producers. They found that reducing BRD would benefit grain and feedstuff producers by USD $493 million over 16 quarters due to increased demand for feedstuffs.

A smaller subset of studies directly examines impacts on feed grain companies. Within this line of literature, Pendell and Cho (2013) study the impacts of FMD outbreaks in Korea on the stock market returns for three Korean animal feed companies. They find the feed companies experienced significant negative reactions two days after Korean FMD reports, due to reductions in those companies' revenues. Finally, perhaps most related to our purposes, Schmidt and Mattos (2021) use a generalized autoregressive conditional heteroskedasticity (GARCH) model to show that the recent African Swine Fever (ASF) outbreak in China had a negative impact on Brazilian soybean price returns.

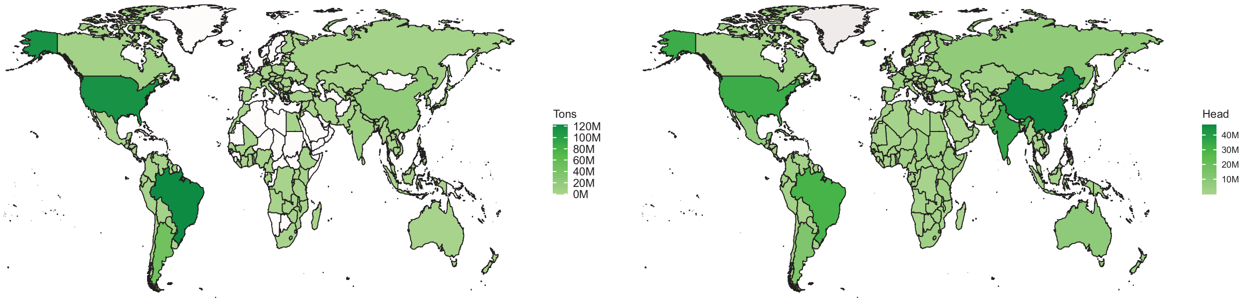
3 Data

We collect annual information on bilateral soybean trade flows between all countries. We match this trade data with annual, country-level information on soybean and livestock (i.e., cattle, swine, and poultry) production and disease-specific livestock mortality. We also collect data for various additional model controls. These data are described below.

Bilateral Soybean Trade Data: Bilateral soybean trade data are obtained at the four-digit HS-level (HS 1201) from UN Comtrade for all countries between 1995–2020. Over our sample period, China is the largest soybean importer, accounting for 10–20% of global imports. Other major soybean importers include Argentina, Mexico, and Thailand.

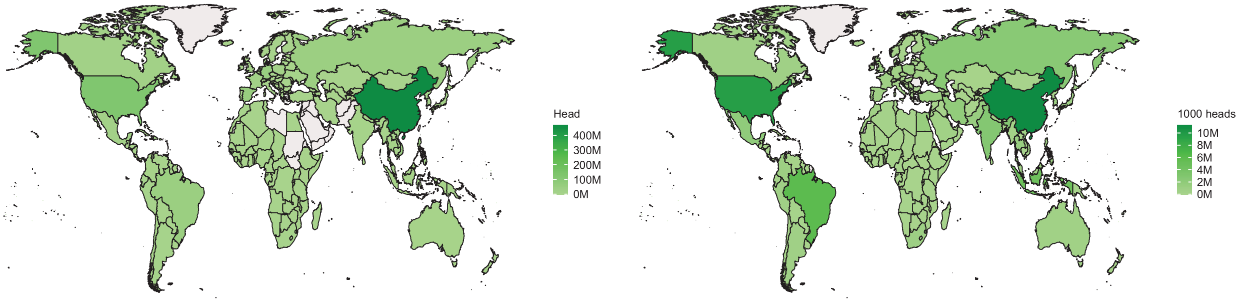
Soybean and Livestock Production Data: We collect annual, country-level production data for soybeans, meat, and livestock inventory (i.e., cattle, swine, and chicken) for all countries between 1995–2020 from (FAOSTAT, 2023). Meat production data includes the total annual output from both commercial and farm slaughters, measured in the number of animals slaughtered per year. Conversely, the livestock inventory data indicates the total number of animals present in the country at the time of enumeration. Figure 1 summarizes world production of soybeans and meat in 2020. More than 80% of world soybean production occurs in North and South America. The top three global producers are the U.S., Brazil and Argentina. Asia represents another 11% of world soybean production, where the top producers are China and India. China, India, U.S., Brazil, and Argentina are top beef producers, China, U.S., Spain, Germany, and Brazil are top pork producers, and China, U.S., Brazil, Indonesia, and India are the top chicken producers.

Figure 1: Global Soybean and Livestock Production (2020)



(a) Soybean production

(b) Cattle production



(c) Swine production

(d) Poultry production

Notes: Figure shows (a) soybean, (b) cattle, (c) swine, and (d) poultry production in 2020. Underlying data are obtained from FAOSTAT (2023).

Disease-Specific Livestock Mortality Data: We construct annual, disease-specific data on livestock mortality for each country using information from the World Animal Health Information System (WAHIS).[2] The WAHIS database—maintained by the World Organization for Animal Health (WOAH)—records the occurrence of animal diseases in different parts of the world. Outbreak data are available starting from 2005 and include new outbreaks, number of susceptible animals, number of cases, number of animals killed and disposed, number of animals slaughtered during outbreaks, number of animal deaths, and number of animals vaccinated in each administrative region of a country. We compile information from each of these analytic reports to construct livestock mortality counts by disease, by country from 2005–2020.[3] Poultry mortality data are not separated from the mortality of other farmed birds in the WAHIS database. Thus, we cannot distinguish disease outcomes for, say, farmed ducks or geese from disease outcomes specific to poultry. For the purposes of our analysis, we assign the mortality of all farmed birds to poultry. This certainly overestimates poultry disease mortality. However, because poultry represents the largest farmed avian species, the extent of over-estimation may be minimal.

Figure 2 summarizes the incidence of global animal disease as a percentage of global livestock production. According to our data, approximately 0.01% of total cattle production, 0.05% of total swine production, and 0.03% of total poultry production were lost due to reportable animal diseases for the period 2005–2020. This estimate does not include losses due to endemic disease, management, condemnations, or predation. Figure 3 summarizes disease-specific mortality and total losses over time for each of the three livestock species

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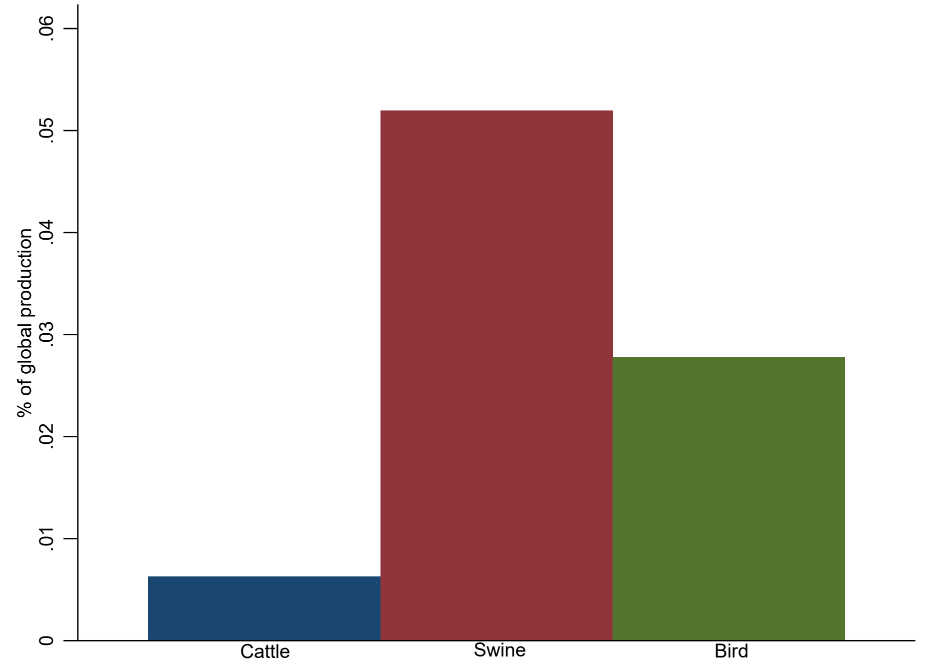
[2] Note that the diseases considered here correspond to diseases on WOAH's reportable list. Many endemic diseases like bovine respiratory disease are not included but also have an impact on mortality and morbidity. We believe it is appropriate to exclude these diseases from the analysis. The endemic nature of these diseases means that they are in a quasi-long-run equilibrium (i.e., approximately the same number of cases each year). Accordingly, the soybean market adjusts to these types of disease in terms of planting decisions, trade search costs, and expected prices. Accordingly, we do not believe they generate substantial costs to upstream soybean trade.

[3] For each administrative region, our mortality measure is obtained as the maximum value of two variables from the WAHIS report: (1) number of animals killed and disposed and (2) number of animal deaths. We suspect that—in some instances—animals culled in an administrative region once a disease is detected are "double counted" in the number of animal deaths. Thus, we take the maximum value of variables (1) and (2) for the purpose of being conservative.

for the period 2005–2020. A few diseases account for the vast majority of animal losses: Foot-and-mouth disease (FMD) for cattle accounts for 94% of total cattle death; African swine fever (ASF) accounts for 75% of total swine death; and 3) Highly pathogenic avian influenza (HPAI) accounts for 97% of total bird death.

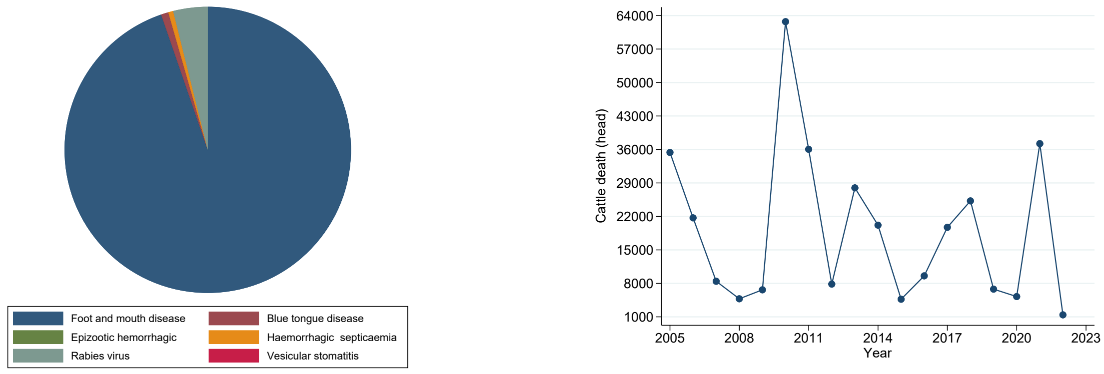
Figure 2: Global Animal Disease Mortality as a Percentage of Production



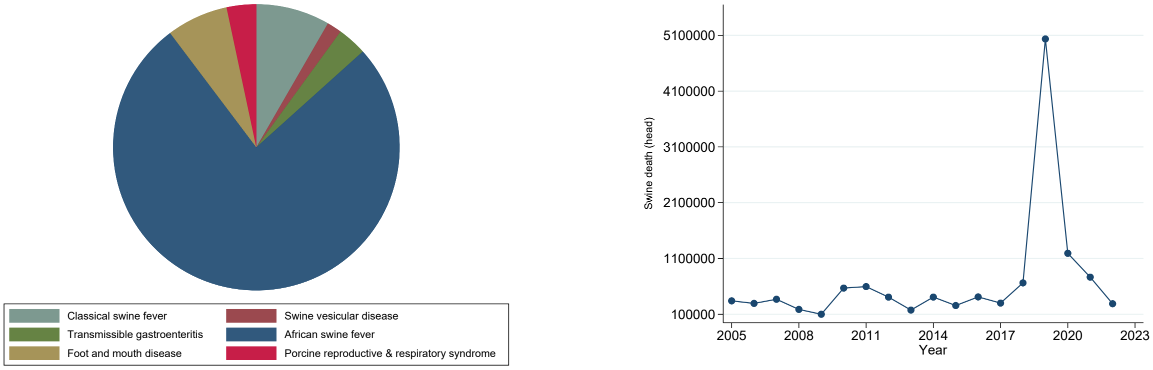
Notes: Figure summarizes the total number of animal deaths for the period 2005–2020 as a share of the global livestock production. Underlying data from FAOSTAT and the WAHIS database.

Additional Control Variables: Annual, country-level GDP (in U.S. dollars) are obtained from the World Development Indicator database. We collect bilateral information on distance, contiguity, the presence of a common official language, and colonization by the same country between country pairs used in the dataset from Centre d'Etudes Prospectives et d'Informations Internationales (CEPII).

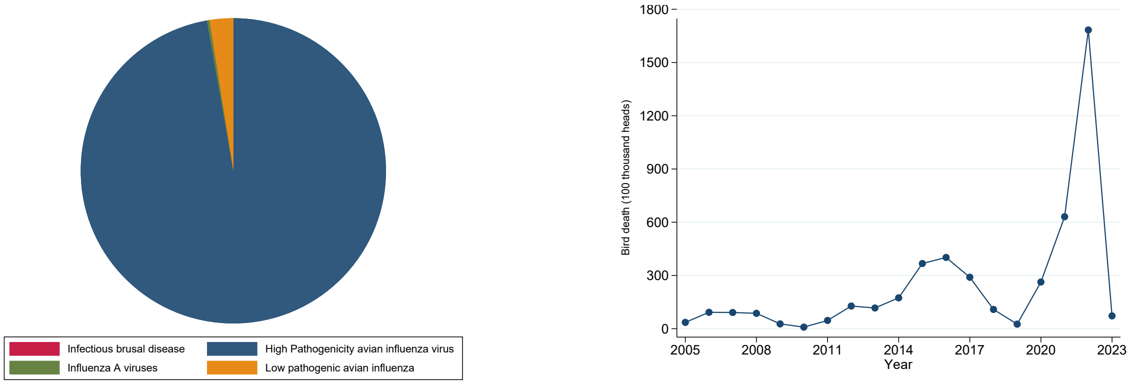
Figure 3: Disease-Specific Animal Losses and Mortality over Time



(a) Disease-Specific Cattle Losses (b) Total Cattle Mortality



(c) Disease-Specific Swine Losses (d) Total Swine Mortality



(e) Disease-Specific Bird Losses (f) Total Bird Mortality

Notes: Figure summarizes disease-specific mortality and total losses over time for each of the three livestock species for the period 2005–2020. Underlying data from the WAHIS database.

4 Methods

We cannot directly estimate the impacts of animal-disease-generated mortality on soybean trade for the reason that we do not observe soybeans *not* traded as a result of animals that do not exist (but otherwise would have in the absence of disease). Accordingly, we must take a slightly less direct approach to the estimation. Using the data described above in Section 3, we employ a two-step procedure to deduce the impacts of animal disease on upstream soybean trade. Our rationale is straightforward: To the extent that these countries depend on soybean imports to feed their domestic livestock populations, we expect a higher value of soybean exports into a country when its livestock populations are higher. If an animal disease outbreak reduces the number of livestock animals in the country, we anticipate stakeholders to respond by importing less soybeans. We seek to quantify this relationship.

To do so, we first use a standard, econometric gravity model to empirically estimate the relationship between observed trade and livestock production patterns (accounting for each country's economic masses and trade frictions). We then conduct a counterfactual analysis using our estimated gravity relationships to assess the value of lost soybean trade due to animal disease based on the disease-specific WAHIS animal mortality data. Similar two-step approaches have been used in various contexts, including *inter alia* the long-run trade implications of food safety scandals (Schaefer, Scheitrum and Nes, 2018), imposition of retaliatory tariffs (Choi and Lim, 2023; Yu, Villoria and Hendricks, 2022), and approval of new genetically engineered seed varieties (Nes, Schaefer and Scheitrum, 2022). To our knowledge, we are the first to use such an approach to analyze the impacts of animal disease on upstream stakeholders. Section 4.1 presents our gravity model, and Section 4.2 describes our counterfactual analysis to assess disease-driven trade losses.

4.1 Reduce-Form Econometric Gravity Model

We quantify the relationship between bilateral soybean trade and livestock production patterns in importing countries using the following reduced-form econometric gravity specification:

$$V_{iet} = \exp[\pi_{it} + \theta_{et} + \mu_{ie} + \beta_1 \ln(C_{it}) + \beta_2 \ln(H_{it}) + \beta_3 \ln(B_{it}) + \beta_4 \ln(A_{et})]\epsilon_{iet} \tag{1}$$

where dependent variable V is the value of soybeans exported by country e to importing country i in year t (specified in levels). Explanatory variables C, H, and B, respectively, correspond to the produced amount of cattle,[4] hogs, and poultry measured in millions of head in importing country i in year t. Explanatory variable A corresponds to the volume of soybean production (measured in million tonnes) in exporting country e in year t. This variable is one measure of the exporting country's "economic mass" in the international soybean market. Consistent with Silva and Tenreyro (2006), all of these explanatory variables are expressed via natural logarithmic transformation.

Multilateral Resistance Terms: The terms π_{it} and θ_{et} on the right-hand side of equation (1) characterize multilateral resistance (MR)—i.e., product-specific barriers to trade that each country faces with all its trading partners in a given year. One common approach to account for these MR terms is to include in the model a series of importer-product-time and exporter-product-time fixed effects (Yotov et al., 2016). However, in our case, our explanatory variables of interest (C, H, and B) would not be identified because they would be completely absorbed by the exporter-side MR fixed effects. Accordingly, we follow the approach proposed by Baier and Bergstrand (2009).

We construct MR terms based on first-order Taylor expansion on the distance between two countries (MR_{dist}), presence of a colonial relationship (MR_{colony}), and common language (MR_{coml}). To do so, we calculate the weighted average of GDP share for importing country

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[4] Note that the number of head of cattle slaughtered for meat production primarily covers beef cattle, but also includes some dairy cattle removals if they are slaughtered for meat.

i and exporter country e as:

$$\theta_j = \frac{GDP_i}{Y_w}, \theta_k = \frac{GDP_e}{Y_w} \tag{2}$$

where Y_w is the world's total GDP each year. Then, MR terms MR_{dist}, MR_{colony}, and MR_{coml} are calculated as:

$$ln\pi_i = \sum_{j=1}^{N} \theta_j lnt_{ij} + \sum_{k=1}^{N} \theta_k lnt_{kl}, i = 1, ..., N \tag{3}$$

where the MR term for distance, colony, and common language in country i is calculated as $\sum_{j=1}^{N} \theta_j \ln t_{ij}$ in which θ_j is the portion of GDP of country 'j' (j=i= importer) divided by total world GDP (Y_w), and multiplied with lnt_{ij}; t= distance, colony and common language, between the two countries; importer i and exporter e, $\sum_{k=1}^{N} \theta_k \ln t_{kl}$ in which θ_k is the portion of GDP importer country 'k' (k=e= exporter) divided by the total world GDP and multiplied with log of t_{kl}, which are distance, colony and common language, between the two countries. If the GDP-share-weighted average of the gross trade cost facing importer country i across all exporters e is higher, the greater the overall MRT terms in importer i.

Summary Statistics: Table 1 reports summary statistics for the data used to fit the model described in equation (1). Model estimation and robustness checks are conducted using two datasets from FAOSTAT: meat production and livestock inventory. Our datasets include 108, 646 observations involving 179 exporting countries and 192 importing countries between 1995–2020. As shown in the Table, the average value of bilateral soybean trade was approximately $246 million per year. On average, soybean importing countries produce 2.5 million heads of cattle (C), 13.1 million head of swine (H), and 498.5 million head of poultry (B). Additionally, the average livestock inventory in these importer countries consists of 10.03 million head of cattle (C), 9.18 million head of swine (H), and 159.61 million head of poultry (B). The average soybean exporter produced approximately 7 million tonnes of soybeans per year.

Estimation Procedure: We estimate the model via Poisson Pseudo-Maximum Likelihood

Table 1: Summary Statistics (Observations = 108,646)

Variable	Units	Mean	Std. Dev.	Min	Max
Dependent variables					
V_{iet}	million USD	8.07	245.64	0	28843.06
Q_{iet}	million tonnes	19.23	0	66080	
Explanatory variables					
A_{et}	million tonnes	6.95	20.58	0	121.80
Meat production					
C_{it}	million head	2.49	6.37	0	46.71
H_{it}	million head	13.10	57.35	0	744.92
B_{it}	million head	498.54	1335.14	0	11261.99
Livestock inventory					
C_{it}	million head	10.03	26.03	0	218.19
H_{it}	million head	9.18	42.42	0	486.74
B_{it}	million head	159.61	506.39	0	5302.72
Disease-Driven Animal Mortality					
Cattle					
FMD-Specific Losses	thousand head	2.47	6.65	0	37.41
Total Losses	thousand head	2.61	6.79	0	37.41
Swine					
ASF-Specific Losses	thousand head	70.53	397.42	0	3962.54
Total Losses	thousand head	94.47	439.16	0	4284.20
Bird					
HPAI-Specific Losses	million head	4.30	12.16	0	76.78
Total Losses	million head	4.43	12.30	0	76.94

Notes: Table reports summary statistics for the bilateral trade value (V_{iet}), trade volume (Q_{iet}), soybean production, livestock inventory and production data used to fit the model described in equation (1) and the animal disease mortality data used to conduct the counterfactual analysis described in Section 4.2. Underlying data are obtained from UN Comtrade, FAOSTAT, and the WAHIS database.

(Silva and Tenreyro, 2010; Weidner and Zylkin, 2021). Standard errors are clustered at the country pair (importer-exporter) level.

4.2 Counterfactual Simulation Analysis

The parameters obtained by estimating equation (1) approximate the real-world, data-generating process between importing country livestock inventories and corresponding bilateral soybean trade outcomes. Using this estimated data-generating process, we implement a counterfactual simulation analysis to deduce the impacts of international animal disease outbreaks on soybean trade outcomes between 2005–2020.

To do so, we first calculate the actual, predicted bilateral trade outcomes (denoted $\hat{V}_{iet}^{Actual}$) based on observed livestock inventories and other explanatory variables in equation (1). We then construct alternative livestock inventories (denoted C_{it}^{CF} for cattle, H_{it}^{CF} for swine, and B_{it}^{CF} for poultry) for all importing countries under the hypothetical reality that no disease outbreaks occurred over our sample period. So, for example, counterfactual cattle inventories (C_{it}^{CF}) in importing country i at a given time t are the number of actual cattle holdings in the country plus the number of cattle that died as a result of an animal disease outbreak (denoted $CMort_{it}$). Thus, $C_{it}^{CF} = C_{it} + CMort_{it}$.

We then generate counterfactual bilateral soybean trade outcomes (denoted $\hat{V}_{iet}^{CF}$) using the parameters of the estimated data-generating process and the counterfactual animal inventories.[5] All other explanatory variables from equation (1) remain unchanged.

We calculate the impacts of international animal disease outbreaks on bilateral soybean trade outcomes as the difference between counterfactual and actual predicted soybean trade outcomes ($\widehat{Impact}_{iet} = \hat{V}_{iet}^{CF} - \hat{V}_{iet}^{Actual}$). Thus, the total soybean trade losses experienced by a given exporter in a given year due to animal disease are $\sum_i \widehat{Impact}_{iet}$ and the total losses for a given importer are $\sum_e \widehat{Impact}_{iet}$. We implement this analysis to assess the soybean trade impacts of all animal diseases, as well as species-specific trade impacts for cattle, swine, and poultry, and disease-specific impacts for FMD, ASF, and HPAI.

5 Results

Gravity Results: Table 2 presents the outcomes of our reduced-form gravity model estimation. Turning to our parameters of interest, we see that—as expected—an increase in the meat production; beef, pork, chicken, in an importing country corresponds to an increase

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[5] As a point of clarification, note that we do not re-estimate equation (1). Rather, we generate these counterfactual trade outcomes using our original gravity parameter estimates by fitting the predictions with the counterfactual animal inventories.

in its import of soybeans in all of these models. The results in the Table suggest that a 1% increase in domestic cattle head is associated with a 0.34% increase in bilateral soybean imports. This effect is statistically significant at the 10% level.

Table 2: Gravity Model Results

VARIABLES	Point Est.	Std Error
Ln Cattle$_i$	0.341*	0.193
Ln Swine$_i$	0.089*	0.052
Ln Poultry$_i$	0.622**	0.250
Ln Soy Production$_e$	1.054***	0.337

Standard errors are clustered at the importer-exporter level.
*** p<0.01, ** p<0.05, * p<0.1

Perhaps surprisingly, the magnitude of the estimated relationship is more muted for swine. According to Table 2, a 1% increase in swine inventories corresponds to a 0.09% increase in soybean imports (statistically significant at the 10% level). In contrast, the results for poultry inventories exhibit the strongest relationship with bilateral soybean trade outcomes—both in terms of statistical significance and economic magnitude. Our results suggest that a 1% increase in poultry numbers is associated with a 0.6% increase in soybean imports (statistically significant at the 1% level).

Impacts of Animal Disease on Upstream Soybean Trade: As described in Section 4.2, we fit expected trade outcomes based on the data-generating process estimated in Table 2 and the counterfactual trade outcomes that would have occurred under the assumption that importers experienced no animal mortality due to disease outbreaks. The difference between these two estimates represents the impacts of animal disease outbreaks on international soybean trade. Table 3 presents our estimates of these impacts, evaluated from the perspective of the "average" importer, the "average" exporter, and the global trade market over our sample period.

As shown in Table 3, we find that the value of foregone soybean trade due to animal disease outbreaks was approximately $4.9 billion over our sample period. For context, from

Table 3: Impacts of Animal Disease on Upstream Soybean Trade

	Importer Losses		Exporter Losses		Global Losses	
Impact measure	Mean (Million USD)	Trade Share (% of Imports)	Mean (Million USD)	Trade Share (% of Exports)	Total (Million USD)	Trade Share (% of Total Trade)
Species-Specific Impacts						
Cattle diseases	23.55	0.50	25.52	1.97	4568.71	0.59
Swine diseases	0.44	0.03	0.47	0.02	84.62	0.01
Poultry diseases	1.26	0.04	1.36	0.04	243.85	0.03
Disease-Specific Impacts						
FMD	21.30	0.46	23.08	1.68	4131.97	0.54
ASF	0.09	0.01	0.09	0.01	16.46	0.002
HPAI	1.14	0.04	1.24	0.04	221.36	0.029
Total impact	25.36	0.57	27.49	2.03	4920.5	0.64

Notes: Table presents our estimates of the impacts of animal disease on upstream soybean trade, evaluated from the perspective of the "average" importer, the "average" exporter, and the global trade market over our sample period. To assess these impacts, we fit expected trade outcomes based on the data-generating process estimated in Column (1) of Table 2 and the counterfactual trade outcomes that would have occurred under the assumption that importers experienced no animal mortality due to disease outbreaks. The difference between these two estimates represents the impacts of animal disease outbreaks on international soybean trade.

2005 to 2020, the total value of soybean trade in the world market was $764 billion. Thus, our estimated impacts represent slightly less than 1% of global trade during that period.

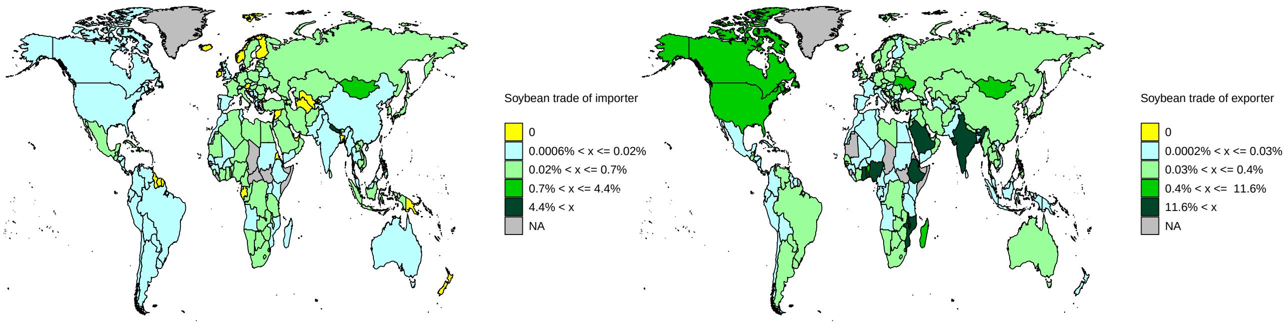
Referring to our species-specific estimates, we see that cattle diseases are by far the most disruptive events for soybean trade. We find that cattle diseases caused approximately $4.5 billion worth of lost soybean trade over our sample, compared with $84 million and $243 million in losses resulting from swine and poultry diseases, respectively. These losses represent 0.59%, 0.01%, and 0.3% of total soybean trade. The amount of feed required for cattle is much higher than for a hog or a chicken, as is the value of the animal. Thus, losing cattle can result in a greater financial loss and feed requirement than losing a hog or a chicken. Referring to the disease-specific impacts, we see that FMD represents the primary driver of cattle-disease-driven soybean trade losses ($4.1 billion out of $4.6 billion), ASF represents the majority of swine-disease-driven soybean trade losses ($16 million out of $84 million) and HPAI represents the major driver of poultry-disease-driven soybean trade losses ($221 million out of $243 million).

Referring to the importer-specific losses shown in Table 3, We find that, among the 192 soybean importers in our sample, animal disease decreased soybean imports by an average of $25 million per country over the sample period. However, there was a significant gap between major and small importers. For 2005-2020, soybean imports were quite concentrated, with China accounting for 58% of global imports, thereby standing as the world's top soybean importer. Another 32.5% of the soybean imports were distributed among 16 countries, including Japan, the Netherlands, Germany, Mexico, Spain, Thailand, Indonesia, Egypt, South Korea, and Turkey, among others. The remaining 10% of imports were shared by the other 177 countries. With such concentration, the losses are predominantly borne by the major importers. As illustrated in Figure 4, significant soybean importers, such as China, experienced losses of up to 0.02% of their imports, amounting to approximately 4.5 billion USD. In contrast, smaller importing countries, which also faced import losses of up to 0.02%, saw impacts on a much smaller scale, such as losses amounting to 1,170 USD.

Because the export sector is fairly concentrated, disease impacts are more substantial from the export perspective. Among the 179 exporting countries in our sample, the average trade losses are \$27 million, or approximately 2% of trade over our sample. From 2005 to 2020, Brazil, the US, and Argentina accounted for approximately 87% of the world's total soybean exports, with an additional 10% of the export share being held by four countries: Paraguay, Canada, Uruguay, and Ukraine.

The maps in Figure 4 disaggregate these losses by country, from the perspective of importers in panel (a) and from the perspective of exporters in panel (b). Referring to panel (b), we see that major exporting countries, including Brazil and Argentina, lost as much as 0.4% of exports, whereas the U.S., Canada, and Ukraine lost between 0.5% and 3% of their export potential, with monetary values ranging from 68 million USD to over one billion USD. Finally, the maps in Figures 5 and 6 show the species- and disease-specific impacts of animal disease on upstream soybean trade. Based on these maps, we see that our estimated losses are primarily attributable to cattle disease outbreaks in East Asia and South America.

Figure 4: Impacts of Animal Disease Outbreaks on Soybean Trade, by Country

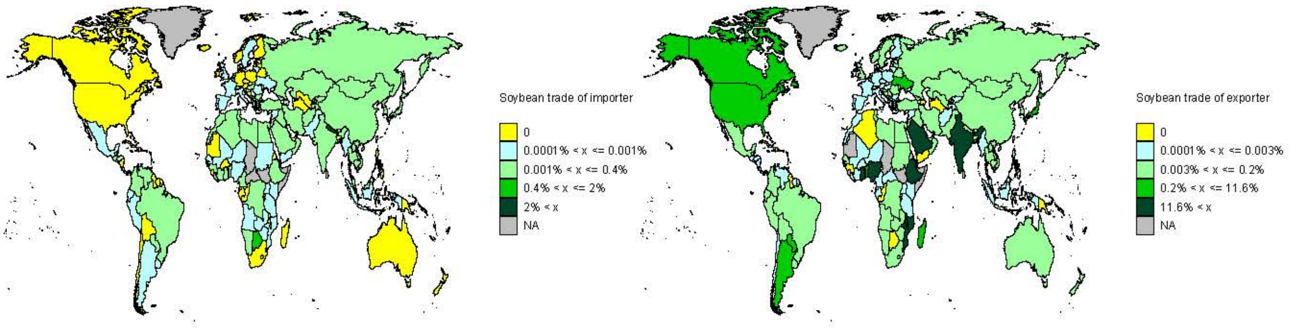


(a) Import-Country-Specific Impacts

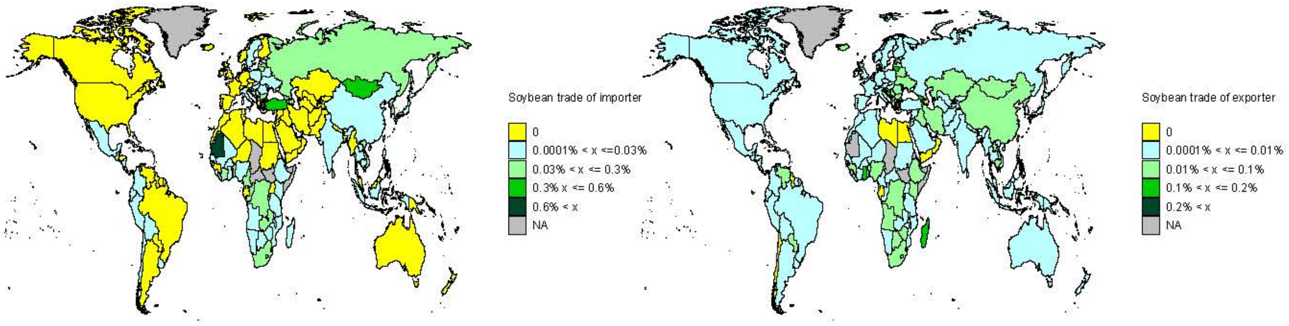
(b) Export-Country-Specific Impacts

Notes: Maps in the Figure show the impacts of animal disease on upstream soybean trade, disaggregated by country. Results are presented from the perspective of importers in panel (a) and from the perspective of exporters in panel (b).

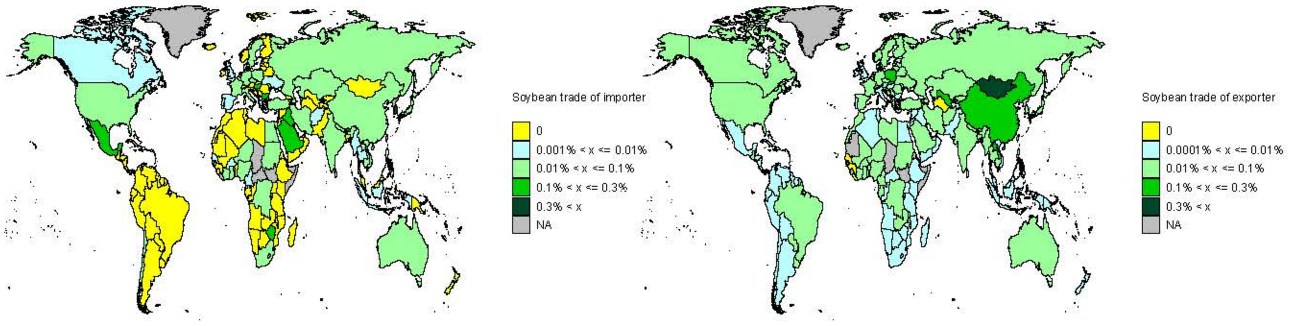
Figure 5: Species-Specific Impacts of Disease Outbreaks on Soybean Trade, by Country



(a) Cattle Disease, Imports (b) Cattle Disease, Exports



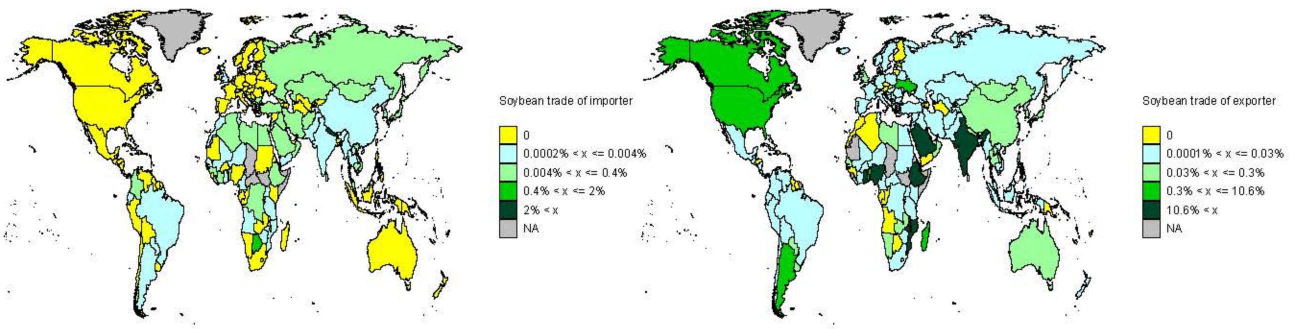
(c) Swine Disease, Imports (d) Swine Disease, Exports



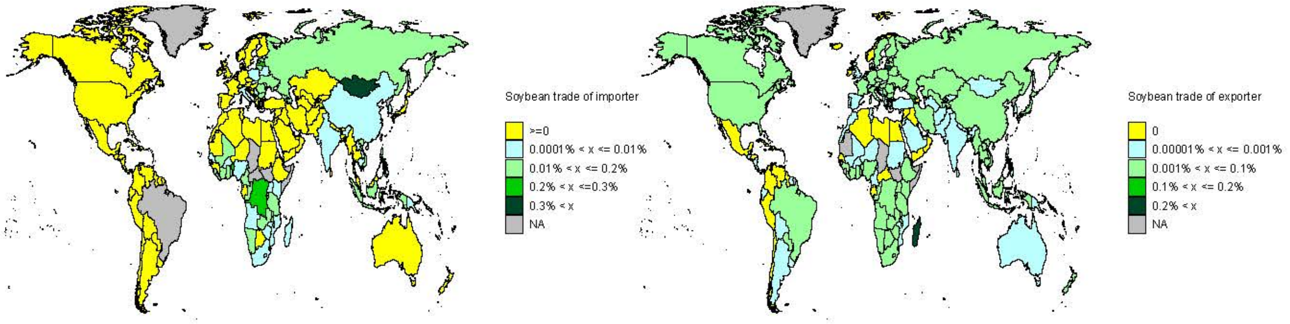
(e) Avian Disease, Imports (f) Avian Disease, Exports

Notes: Maps in the Figure show the species-specific impacts of animal disease on upstream soybean trade, disaggregated by country. Results are presented from the perspective of importers on the left-hand side and from the perspective of exporters on the right-hand side.

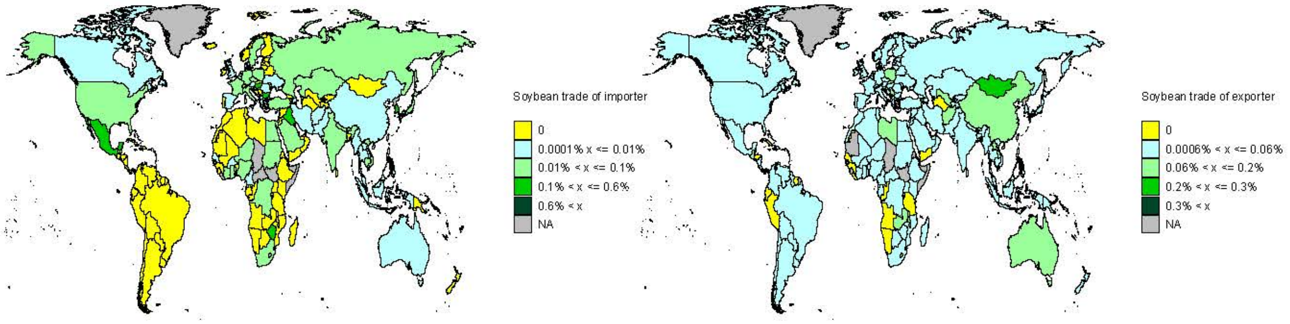
Figure 6: Disease-Specific Impacts of Disease Outbreaks on Soybean Trade, by Country



(a) FMD, Imports (b) FMD Exports



(c) ASF, Imports (d) ASF, Exports



(e) HPAI, Imports (f) HPAI, Exports

Notes: Maps in the Figure show the disease-specific impacts of animal disease on upstream soybean trade, disaggregated by country. Results are presented from the perspective of importers on the left-hand side and from the perspective of exporters on the right-hand side.

6 Model Robustness

In this Section, we conduct a number of additional analyses to gauge the reliability and robustness of our results in estimating the observed relationship between bilateral soybean trade and livestock production patterns. Specifically, we explore the sensitivity of our estimates to alternative model fixed-effects designs, inclusion of additional demand-side "pull" factors, alternative constructions of the livestock variables, alternative constructions of our dependent variable, and alternative definitions of the sample period. Table 4 reports the results of these robustness checks alongside our baseline results for the purposes of comparison. As discussed below, the results of these additional analyses are qualitatively similar to those in the baseline representation.

Table 4: Gravity Model Results—Model Robustness

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Ln Cattle$_i$	0.341*	0.359*	0.340*	-0.246	0.287	0.154
	(0.193)	(0.203)	(0.192)	(0.274)	(0.220)	(0.246)
Ln Swine$_i$	0.090*	0.046	0.090*	0.090	0.053	0.198***
	(0.052)	(0.054)	(0.052)	(0.156)	(0.054)	(0.070)
Ln Poultry$_i$	0.622**	0.532**	0.623**	0.016	0.439*	0.480
	(0.250)	(0.244)	(0.251)	(0.019)	(0.231)	(0.302)
Ln Soy Production$_e$	1.05***	1.11***	1.05***	1.02***	1.16***	1.03***
	(0.226)	(0.243)	(0.225)	(0.228)	(0.225)	(0.297)
Ln Soy Production$_i$			-0.003			
			(0.027)			
GDP	Yes	Yes	Yes	Yes	Yes	Yes
MRT Terms	Yes		Yes	Yes	Yes	Yes
Importer-Exporter FEs	Yes		Yes	Yes	Yes	Yes
Importer FEs		Yes				
Exporter FEs		Yes				
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	108,646	108,741	108,646	107,677	108,646	59,788

Standard errors reported in parentheses are clustered at the importer-exporter level.
*** p<0.01, ** p<0.05, * p<0.1

Alternative Model Fixed Effects Designs: To generate the results in Column (2) of Table 4, we re-estimate equation (1) using an alternative set of fixed effects. In this robustness check, we include importer-specific, exporter-specific, and time fixed effects, and exclude the MRT terms. As shown in the Table, the results of this specification are qualitatively similar to our baseline outcomes. A 1% increase in cattle head corresponds to a 0.36% increase in soybean imports. This effect is statistically significant at the 10% level. The relationship between swine inventories and soybean imports fall in magnitude (relative to our baseline outcomes) to 0.05% and is no longer statistically significant. As with our baseline outcomes, the results for poultry inventories exhibit the strongest relationship with bilateral soybean trade outcomes—both in terms of statistical significance and economic magnitude. A 1% increase in poultry numbers is associated with a 0.5% increase in soybean imports (statistically significant at the 5% level). Finally, as with the baseline outcomes, a 1% increase in domestic soybean production in the exporting country corresponds to an approximate 1% increase in bilateral soybean trade (statistically significant at the 1% level). This is consistent with the notion that international trade markets are often satisfied by the "residual supply” after domestic market needs have been met.

Additional Demand-Side “Pull” Factors: To the extent that soybean production in the importing country is correlated with both domestic livestock numbers and soybean imports from abroad, exclusion of this demand-side “pull” factor could bias results with respect to our explanatory variables of interest. To account for this possibility, we re-estimate equation (1) including soybean production of the importing country as an additional explanatory variable. The results of this analysis are reported in Column (3) of Table 4. The results suggest that exclusion of soybean production in the importing country as an explanatory variable does not meaningfully bias our results. Column (3) reveals that the magnitude and significance level of the relationship between bilateral soybean trade, livestock production in the importing country, and soybean production in the exporting country are nearly identical to those in the baseline model.

Alternative Constructions of the Livestock Variables: Another potential issue concerns our choice of using annual slaughter statistics to represent domestic livestock supply. To assess the sensitivity of our results to alternative constructions of the explanatory variables of interest, we re-estimate equation (1) using total livestock inventories instead of head slaughtered. Column (4) of Table 4 shows the results of this analysis. Comparing these estimates with our baseline outcomes, we see that the coefficient estimates for all variables of interest are statistically indistinguishable from zero. Moreover, the point estimate for our cattle variable is negative.

We offer two possible reasons for these results. First, unlike swine and poultry, which are monogastric species, cattle are ruminants, and grazing serves as one of their primary sources of feed. The cattle inventory data includes animals raised for various purposes, including meat, draft, and breeding. Alternative protein sources might be utilized for cattle apart from beef purpose, reducing the reliance on high-cost imports. Most breeding cattle are primarily grazed with limited protein supplementations. Even in dairy cows, hay and grass are a big part of their dietary needs.

A second potential explanation for these results is that in-country soy production has the potential to either substitute for or diminish soy imports, as leading beef producers like the US and Brazil are also major soybean exporters. The coefficient for swine exhibits a similar trend, and the magnitude of the poultry inventory's coefficient is significantly smaller compared to those in columns (1), (2), and (3). A plausible explanation for the low coefficient value associated with poultry inventory is its shorter production cycle, which allows for up to two cycles annually. Consequently, the amount produced exceeds the inventory for poultry.

Alternative Construction of the Dependent Variable: The gravity model described by equation (1) is estimated with the value of bilateral trade as the dependent variable. While this approach is consistent with the theoretical gravity equation (Silva and Tenreyro, 2006), one potential shortcoming is that—when there is a major animal disease outbreak—global supplies go down, and (thus) commodity prices go up. The potential for attenuation of the estimated effect through global price adjustments may generate a downward bias in our estimates. Accordingly, following Dall'Erba, Chen and Nava (2021) and others, we assess the sensitivity of our results by re-estimating the model using quantity as the dependent variable. As shown in Column (5) of Table 4 shows that the estimates from this robustness check are very similar to our baseline results.

Alternative Definitions of the Sample Period: Finally, due to data availability constraints, there is a mismatch between the sample period used to estimate the gravity relationship (1995–2020) and the sample period used to generate the counterfactual analysis (2005–2020). This is because 2005 is the earliest year covered by the WAHIS dataset. To ensure this difference in time periods does not bias our results, we re-estimate the gravity model using a sample period consistent with the counterfactual analysis (i.e., 2005–2020). Column (6) of Table 4 shows that the estimates from this robustness check. Point estimates from this analysis are highly consistent with those from the baseline analysis, though we lose statistical significance for cattle and poultry, most likely due to the lower statistical power of the analysis.

7 Policy Implications and Conclusion

Transboundary animal diseases (TADs) have the potential to disrupt the agricultural economy in not just the outbreak country but also upstream in the supply chain. However, the potential indirect impacts on upstream input suppliers have received limited attention in the animal health literature. Our research fills that gap, investigating the upstream impacts of global, high-consequence animal disease outbreaks on the international soybean market. We employ a two-step procedure to deduce the impacts of animal disease on upstream soybean trade. We first use a standard, econometric gravity model to empirically estimate the relationship between observed trade and livestock production patterns (accounting for each country's economic masses and trade frictions). We then conduct a counterfactual analysis with our estimated gravity relationships to assess the value of lost soybean trade using a global repository of disease-specific animal mortality data.

Our results indicate that between 2005 and 2020, animal disease outbreaks have cost the international soybean market approximately $5 billion in lost trade. The average exporter loses as much as 2% of its export potential each year. These losses are primarily attributable to cattle disease outbreaks in East Asia and South America. On a value basis, cattle represent the largest portion of global livestock assets and are often considered a measure of wealth (Schrobback et al., 2023). As one of the most prominent diseases of cattle, foot-and-mouth disease alone has cost the soybean trade market approximately $4 billion in lost trade over our sample period.

Policy implications are many. Globally, animal health policies have focused primarily on compensation to producers of affected livestock, which may include indemnity for animals that die or are depopulated for disease control. Producers directly affected by TADs may also receive compensation for market disruptions or decontamination of premises. However, few policies address the risk animal diseases pose to upstream suppliers. Crop insurance programs, if available, may protect grain producers against price declines. However, crop insurance is unlikely to address additional costs of storage or quality loss for grain that must be stored for longer periods of time.

After the COVID-19 pandemic disrupted supply chains globally, several prominent governments responded with policy interventions. These interventions may provide a precedent for the development of supply chain disruption interventions in other high-consequence events like TAD outbreaks. For example, price declines for upstream feed grain industries such as those found in this study could be partially offset through stocks. Countries may buy excess grains to place in government stocks when normal marketing channels are disrupted; those stocks can later be disbursed through food programs or other timely mechanisms. This strategy was utilized in the U.S. in 2020, when the USDA announced in April that they would spend $3 billion to purchase fresh produce, meat and dairy (USDA, 2020). Those products were subsequently dispersed in a food security program. A similar structure could be used to help offset losses for grain producers as needed.

More generally, governments are funding ways to help companies shore up their supply chain vulnerabilities. These broader efforts to enhance supply chain resilience would subsequently be of benefit in an animal disease-related disruption as well. The European Parliament noted the need to enhance the resilience of global supply chains (Szczepanski, 2021), and the policy options suggested could offset losses such as those found in this study as well.

Further, the results of this study would help identify appropriate levels of funding that might be requested to offset part of the grain sector loss during a TAD outbreak. The Government Accountability Office (GAO) analyzed the Market Facilitation Program (MFP) of 2018 and 2019—a program offset grain producer losses due to retaliatory tariffs in the US-China Trade War—and concluded that the MFP overpaid certain categories of farmers because initial losses were overestimated (United States Government Accountability Office, 2022). Our study improves the understanding of potential loss levels for grain producers in the event of a U.S. or global TAD, which may extend beyond the coverage of crop insurance or other price loss programs.

As global populations and income levels rise over the next two decades, so too will the demand for animal-sourced foods (Data Bridge, 2021; Impactful Insights, 2022). In countries that have undeveloped areas, rising meat demand may force production onto wildlife habitats or other undeveloped lands, which may lead to increased potential for zoonotic disease spillover and environmental damage. In countries that do not have much additional land for agricultural production, rising meat demand could lead to increases in animal stocking densities, and consequently the potential for rapid disease spread in animal populations, as well as increased reliance on imports. Together these factors could spawn increases in the propensity of outbreak and the scale of mortality for many livestock diseases. Alongside these demand-side pressures, changes in long-term climate conditions may also lead to increases in external disease pressures. As disease-carrying insects or wildlife change their range of habitat, disease exposure can occur in previously unexposed animal populations. Policymakers considering the trade-offs between disease mitigation and disease control must consider not only the immediate impacts of the disease on stakeholders in livestock markets, but also players in up- and downstream markets, given the modern integration of international supply chains.

However, we caution that our findings are not without limitations. In some sense, our findings almost certainly *under*-estimate the impacts of animal disease outbreaks on upstream markets. While we believe our analysis relies on the best data available with respect to disease mortality, it is necessarily based on voluntary reports made by individual governments (with imperfect surveillance abilities) to the World Organization for Animal Health. Thus, our dataset almost certainly undercounts the true mortality associated with animal disease. Further, our estimates do not include the production losses associated with illness (morbidity) in livestock, which is commonly experienced with TADs that do not result in high mortality rates (such as FMD) and when disease response does not include de-population. These morbidity losses are not included due to the lack of available consistently measured data on production impacts, but could be included in future research as global efforts to generate consistent morbidity estimates advance. Finally, because our methodology measures only the relationship between the occurrence of outbreaks and contemporaneous changes in trade, we do not measure the duration and intensity of post-outbreak conditions. We leave it to future researchers to make inroads on these issues.

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