Essays on the economic burden of animal diseases

by

Takesure Tozooneyi

B.S., University of Zimbabwe, 2014
M.S., University of Zimbabwe, 2017

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2024

Abstract

Essay 1: The potential economic welfare effects of African Swine Fever on the U.S. swine supply chain

African Swine Fever (ASF) is a deadly viral disease of swine that often leads to substantial economic losses due to the death of animals, the cost of control measures, and loss of trade. The U.S. pork sector, a major component of the agricultural economy, remains vulnerable to ASF. Although the disease has never been detected in the United States, understanding its potential economic impacts is crucial for preparing and prioritizing animal health investments. Using an Equilibrium Displacement Model (EDM) adapted to incorporate the cull hog sector and live hog trade, we quantify the economic welfare impact of hypothetical ASF outbreaks under varying supply, demand, and export shock scenarios. Our analysis reveals that the potential economic losses vary significantly depending on the severity of the outbreak and the resulting market shocks. Small outbreaks confined to specific regions may result in moderate welfare declines, while large-scale outbreaks with substantial export losses could have severe economic impacts across the entire supply chain. The analysis indicates losses ranging from $277 million to $4,077 million across four quarters, primarily driven by losses in the weaner and feeder pig segments. These findings underscore the importance of strengthening biosecurity measures, diversifying export markets, and developing rapid response protocols to mitigate the adverse effects of ASF.

Essay 2: How Important are Trade Agreements during Poultry Disease Events?

In recent times, international trade in livestock and livestock products has witnessed remarkable growth, driven by rising global demand for animal-sourced foods. However, contagious animal diseases are increasingly influencing trade volumes and patterns. Bilateral frameworks, such as Trade Agreements (TAs), can be crucial in smoothening trade during animal health crises. This study examines the role of TAs in mitigating the trade effects of Highly Pathogenic Avian Influenza (HPAI) and Newcastle Disease (ND) on poultry trade. Utilizing a comprehensive dataset of 212 countries engaged in poultry trade, we employed panel gravity models to assess the role of TAs. The results show that while TAs generally promote trade, they do not mitigate the contemporaneous effects of HPAI on poultry trade, but they do for ND. Product-specific analysis reveals heterogeneity in how TAs help sustain trade during outbreaks of both HPAI and ND. Moreover, TA members experience a quicker rebound in trade following disease events. These findings emphasize the importance of TAs in enhancing the resilience of international trade networks during animal health emergencies.

Essays on the economic burden of animal diseases

by

Takesure Tozooneyi

B.S., University of Zimbabwe, 2014
M.S., University of Zimbabwe, 2017

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2024

Approved by:

Major Professor
Dr. Dustin L. Pendell

Copyright

Abstract

Essay 1: The potential economic welfare effects of African Swine Fever on the U.S. swine supply chain

African Swine Fever (ASF) is a deadly viral disease of swine that often leads to substantial economic losses due to the death of animals, the cost of control measures, and loss of trade. The U.S. pork sector, a major component of the agricultural economy, remains vulnerable to ASF. Although the disease has never been detected in the United States, understanding its potential economic impacts is crucial for preparing and prioritizing animal health investments. Using an Equilibrium Displacement Model (EDM) adapted to incorporate the cull hog sector and live hog trade, we quantify the economic welfare impact of hypothetical ASF outbreaks under varying supply, demand, and export shock scenarios. Our analysis reveals that the potential economic losses vary significantly depending on the severity of the outbreak and the resulting market shocks. Small outbreaks confined to specific regions may result in moderate welfare declines, while large-scale outbreaks with substantial export losses could have severe economic impacts across the entire supply chain. The analysis indicates losses ranging from $277 million to $4,077 million across four quarters, primarily driven by losses in the weaner and feeder pig segments. These findings underscore the importance of strengthening biosecurity measures, diversifying export markets, and developing rapid response protocols to mitigate the adverse effects of ASF.

Essay 2: How Important are Trade Agreements during Poultry Disease Events?

In recent times, international trade in livestock and livestock products has witnessed remarkable growth, driven by rising global demand for animal-sourced foods. However, contagious animal diseases are increasingly influencing trade volumes and patterns. Bilateral frameworks, such as Trade Agreements (TAs), can be crucial in smoothening trade during animal health crises. This study examines the role of TAs in mitigating the trade effects of Highly Pathogenic Avian Influenza (HPAI) and Newcastle Disease (ND) on poultry trade. Utilizing a comprehensive dataset of 212 countries engaged in poultry trade, we employed panel gravity models to assess the role of TAs. The results show that while TAs generally promote trade, they do not mitigate the contemporaneous effects of HPAI on poultry trade, but they do for ND. Product-specific analysis reveals heterogeneity in how TAs help sustain trade during outbreaks of both HPAI and ND. Moreover, TA members experience a quicker rebound in trade following disease events. These findings emphasize the importance of TAs in enhancing the resilience of international trade networks during animal health emergencies.

Table of Contents

List of Figures

List of Tables

Acknowledgements

The journey to completing my Ph.D., culminating in this dissertation, would not have been possible without the unwavering guidance and strength bestowed upon me by God Almighty. My family's role in this journey has been nothing short of monumental; their emotional support and constant encouragement sustained me through what was undoubtedly the most challenging phase of my life.

I am deeply grateful to the U.S. Embassy staff in Harare, Zimbabwe, for their invaluable guidance during my Fulbright Scholarship application. Their support and belief in my potential opened the doors to Kansas State University. The generosity of both the Fulbright Scholarship and my department, through their financial support, was crucial in making this journey possible.

I am profoundly indebted to my major advisor, Dustin Pendell, for his exceptional mentorship, generosity, and kindness. Dustin, you introduced me to the fascinating world of Animal Health Economics, offered me a multitude of opportunities, and exhibited remarkable patience during the numerous times I found myself at a crossroads in my dissertation. Working with you not only expanded my academic horizons but also provided me with an exemplary model of mentorship.

I want to extend my sincere gratitude to my committee members, Nelson Villoria, Glynn Tonsor, and Michael Sanderson, for their invaluable feedback and guidance throughout this process.

I am immensely grateful to the Bridges International community at Kansas State University, who became my family away from home, providing unwavering social and spiritual support. My story would be incomplete without acknowledging the vital emotional and social support I received from some close friends. Our bond, strengthened through our Friday night

social gatherings, along with numerous adventures across various U.S. states, fulfilled my deep-seated passion for travel and exploration. The African Students Union also deserves mention for allowing me to experience Africa away from Africa.

Finally, I extend my heartfelt thanks to my entire cohort, whose support, collaboration, and camaraderie have been pillars of strength throughout my Ph.D. journey. Their insights and companionship have enriched my experience in countless ways.

Dedication

To my entire family.

Chapter 1 - Introduction

Animal diseases have nuanced effects on agricultural productivity, food security, and economic stability. Outbreaks of infectious diseases in livestock can lead to catastrophic economic impacts, disrupting production, consumption, supply chains, and markets at both domestic and international levels. Globally, an estimated $300 billion is lost annually due to livestock diseases (WOAH, 2024). Understanding the economic impacts of these diseases, as well as the optimal control and mitigation strategies, is essential for prioritizing investments in animal health. Diseases affecting pork and poultry are particularly of paramount economic importance due to the large contribution these sectors make to the global supply of animal-sourced foods. Globally, pork is the most widely consumed meat, accounting for 36% of total meat consumption followed by poultry at 33% (USDA, 2024).

In the United States, pork production represents an important part of the agricultural economy, contributing over $62 billion in value added (NPPC, 2023). Disease outbreaks in the U.S. swine sector could result in substantial economic losses. Notable examples include Porcine Epidemic Diarrhea Virus (PEDV) and Porcine Reproductive and Respiratory Syndrome (PRRS), two of the costliest diseases affecting the U.S. swine sector. PEDV, which first appeared in the United States in 2013, caused severe piglet losses and a 4.6% reduction in commercial hog slaughter by August 2014 (Schulz & Tonsor, 2015). PRRS, first detected in the 1980s, continues to cause annual losses, costing U.S. swine producers an estimated $664 million per year (Dee et al., 2023). Although PEDV and PRRS are not transmitted through pork and are not notifiable to the World Organization for Animal Health (WOAH), and therefore do not invoke trade restrictions, they still impact United States exports by driving up domestic prices. For instance, during the 2013 PEDV outbreak, the United States experienced a 2.8% decline in exports due to higher domestic prices (Schulz & Tonsor, 2015).

African Swine Fever (ASF) is one of the most economically devastating diseases affecting swine (Casal et al., 2022). Although ASF has never been detected in the United States, recent outbreaks in the Dominican Republic (Cole & Stepien, 2021b) and Haiti (Cole & Stepien, 2021a) in 2021 marked the first ASF cases in the Western Hemisphere in four decades, heightening concerns over its spread to ASF-free areas, including the United States (Lee et al., 2022). For developed nations like the United States, an incursion of ASF could have catastrophic economic impacts on trade and supply chains, with important implications on national security. ASF is highly contagious and caused by a DNA virus from the *Asfarviridae* family. ASF can result in up to 100% mortality within days among domestic pigs and wild boar. The virus affects animals of all breeds and ages and is known for its resilience in varying environmental conditions. Initially described in Kenya in 1921 by Montgomery, ASF has since spread all over the globe. Transmission mechanisms include direct contact with infected animals, ingestion of contaminated materials, and vectors like soft ticks of the genus *Ornithodoros,* which can harbor the virus for over five years, complicating control efforts. Fomites such as clothing, transport trucks, and feed supplies can also act as sources of infection. Despite extensive research, no effective vaccine exists, making prevention and control challenging, relying on culling infected animals, enforcing strict biosecurity measures, and regulating animal movements.

Outbreaks of ASF often lead to substantial economic losses due to the death of animals, costs of disease control, and loss of trade. Globally, the devasting economic repercussions of ASF are well-documented (Berthe, 2020; Galindo & Alonso, 2017). For example, the 2019 ASF outbreak in China — home to half the world's swine population at that time — caused unprecedented disruptions, leading to the death or culling of millions of pigs and a tripling of pork prices, resulting in monetary damages estimated at $141 billion. In 2019, Vietnam lost 20% of its swine stock within the first five months of the ASF outbreak, with the total economic burden amounting to between $880 million and $4,400 million by the end of the year (Casal et al., 2022). The disease affects not only producers, but also the wider value chain, including traders, slaughterhouses, retailers, and consumers. Internationally, ASF is a notifiable disease as per WOAH due to its potential to disrupt global pork supply and trade. Outbreaks of ASF can lead to substantial trade costs due to loss of export markets. ASF outbreaks may result in adverse consumer reactions over food safety concerns, despite there being no known cases of ASF being transmitted to humans (Casal et al., 2022).

Given the challenges associated with ASF incursions into disease-free areas, it is imperative to anticipate its potential ramifications to inform investments in prevention and response actions. The first essay addresses this by assessing the potential economic welfare implications of hypothetical ASF outbreaks on the U.S. swine supply chain. An Equilibrium Displacement Model (EDM) is developed for the U.S. swine industry, applying different supply, demand, and trade shock scenarios to estimate welfare impacts, shedding light on the potential economic effects on swine producers and pork consumers.

The spread of animal diseases between countries is a major concern. Consequently, international trade in livestock and livestock products is highly sensitive to the occurrence of livestock diseases, as trading partners strive to safeguard domestic production and maintain competitiveness in both domestic and foreign markets. The World Trade Organization (WTO) encourages international cooperation to control the spread as well as mitigate the trade impacts of these diseases. One of its frameworks is the Sanitary and Phytosanitary (SPS) agreement, which ensures that measures related to animal health are science-based and non-discriminatory, to avoid disguised protectionism during animal health emergencies. Bilateral frameworks such as Trade Agreements (TAs) can be important in enhancing the facilitation of SPS measures. The objective of the second essay is to understand how TAs enhance the application of SPSs to smoothen trade under animal health crises. Our focus is on Highly Pathogenic Avian Influenza (HPAI) and Newcastle Disease (ND); two highly contagious poultry diseases known for significant economic trade losses globally.

For disease-free countries, the potential introduction of highly pathogenic poultry diseases is a major cause for concern. Over the last two decades, HPAI and ND have emerged in areas previously free of the diseases through various pathways, including migratory birds, fomites, and infected livestock products. Infected products brought through trade remains one of the biggest risk factors. Certain strains of HPAI are zoonotic and pose serious risks to human health. Between 2003 and July 2023, the WHO recorded 878 human cases of HPAI H5N1, with 458 deaths, resulting in a fatality rate of 52.2% across 23 countries (Charostad et al., 2023). Recent incidents involving wild birds, domestic poultry, and other animals—such as sea lions and minks—along with genetic variations in HPAI H5N1 strains, have raised concerns about the disease's potential transmission to humans (Charostad et al., 2023). In contrast, no known cases of zoonosis have been reported with ND.

Highly pathogenic poultry disease events can have major economic repercussions. The ongoing HPAI outbreak in the United States, which began on February 8, 2022, has become the most severe in the country's history, driven by the H5N1 strain. As of October 15, 2024, 100.8 million birds have been affected across 48 states (USDA – APIHS, 2024). One year after the outbreak, significant trade disruptions were observed: U.S. shell egg exports dropped by 47.0%, turkey meat exports fell by 25.6%, and domestic poultry and egg prices surged (Padilla & MacLachlan, 2023). Similarly, during Europe’s 2020-2021 HPAI season - the most severe on record - over 50 million birds were culled across 37 countries, with France bearing the brunt of the impact (ECDC, 2022). Newcastle Disease outbreaks, while generally less severe, have also caused notable disruptions, such as the 2018 outbreak in California that led to the culling of over 1.2 million birds.

To safeguard both animal and human health, importing countries often impose bans on poultry products from disease-affected regions. In some cases, they may allow treated products at discounted prices. These restrictions vary in scope, covering specific geographic areas (e.g., county, state) and product types (e.g., frozen, fresh, or cooked), and can be in place for varying durations (Johnson et al., 2015). Such trade restrictions are costly for countries that export a large portion of their poultry production. For example, following the onset of the 2022 HPAI outbreak in the United States, over 70 countries promptly imposed import bans on U.S. poultry. However, unlike the 2014-2015 HPAI outbreak, where trade bans were often applied at the national or state level, negotiations in 2022 resulted in more localized (state or county level) restrictions. Major trading partners that enacted bans included China, Taiwan, Mexico, and Vietnam. Similarly, the 2020-2021 HPAI outbreak in the European Union led to import bans from countries such as South Africa, South Korea, China, and the Philippines.

While safeguarding animal and human health remains a priority, balancing disease containment with minimal trade disruptions is key to reducing the overall impact of these diseases. In the second essay, we seek to understand how integration brought about by trade concessions can be key in mitigating trade costs from highly pathogenic poultry diseases. A gravity model was used to measure the efficacy of TAs during outbreaks of HPAI and ND. We used a comprehensive global dataset of 212 countries and conducted the analysis using both aggregated and disaggregated poultry data.

Together, these two essays highlight the burdens that highly contagious animal diseases impose on pork and poultry supply chains. Safeguarding animal health is important for economic and human health considerations. Given how these two are inextricably linked to national security, it is of paramount importance for the United States to be well prepared for these impacts. While the first essay delves into the distributional impacts of ASF on the United States swine industry - to understand who is affected and by how much, the second essay is taking a broader picture look at trade impacts and how they can be mitigated through bilateral cooperation. The findings from these essays offer valuable policy insights for policymakers and industry stakeholders as they consider strategies for developing animal health policies, biosecurity plans, and mitigation measures.

Chapter 2 - The potential economic welfare effects of African Swine Fever on the U.S. swine supply chain

Introduction

African Swine Fever (ASF) is a major transboundary animal disease (TAD) of swine with important economic implications on the consumption, production, and international trade of pig and pig products globally. Its incursion can generate substantial economic losses given its high mortality and consequent distortions of pig markets. These impacts could be devastating for the United States' agricultural economy, where swine production is a key component. In recent years, the United States has consistently ranked among the top two global exporters of pork and pork products, with a global export share averaging 32% (USDA ERS, 2023). Domestically, pork is the third most consumed meat after chicken and beef. Americans consume approximately 52 pounds of pork per capita, which accounts for nearly a quarter of their average annual meat consumption.

Although ASF has not yet been detected in the United States, the swine sector remains vulnerable especially given the globalized nature of meat trade and specific risks such as the introduction of invasive species through waste food from international transportation, which heightens the potential for its incursion. This study assesses the potential economic welfare implications of hypothetical ASF outbreaks on the heterogenous agents along the vertical United States swine supply chain, from farrowing to consumers. Our contribution is to incorporate three critical elements often overlooked in existing economic analyses: the cull hog sector, live hog trade, and detailed segmentation of the hog supply chain - to better understand the welfare impacts of ASF.

To quantify the welfare implications of ASF on each of the agents in the swine supply chain, we adapted an equilibrium displacement model (EDM), which is based on the underlying supply and demand relationships of the United States swine industry. Our model builds on prior efforts in livestock economics (Pendell et al., 2010; Schroeder & Tonsor, 2011; Wohlgenant, 2005) and introduces three key innovations. First, we include the cull hog sector to account for the contribution of the routine culling of 3-6% of sows and boars each quarter, due to health, repopulation efforts, and market conditions. Second, unlike many studies that represent international trade solely through meat products (Pendell et al., 2010; Schroeder & Tonsor, 2011), we explicitly incorporate live swine trade, which is particularly relevant between the United States and Canada, a crucial factor for accurate welfare evaluations. Finally, we expand the hog supply chain from sows to consumers to better illuminate the heterogenous welfare effects among different supply chain agents.

To evaluate the economic impacts of ASF, we generate hog depopulation scenarios using a disease spread model for a hypothetical ASF outbreak in the U.S. Midwest and calibrations informed by the 2018-2019 ASF outbreak in China. We also develop scenarios on export restrictions and adverse consumer reactions based on literature. These scenarios are incorporated into the EDM to capture price and quantity changes for welfare estimation. We consider two main production shock scenarios (e.g., small and large production shocks). Essentially, a shock refers to a reduction in swine production due to death and culling as a result of ASF. The first scenario involves a small outbreak confined to a small Midwest region, lasting less than one quarter, resulting in the loss of 0.044% of swine, and a 20% loss of exports, but no adverse consumer reactions. The second considers a large outbreak with a 7.33% swine loss spanning four quarters, a 1% consumer demand shock, and various export restriction regimes. This approach captures the comprehensive economic impacts of ASF under varying degrees of outbreak severity and market reactions. Our results show potential losses ranging from $277 million to $4,077 million across four quarters, primarily driven by losses in the weaner and feeder pig segments. Large outbreaks with significant export losses result in more severe economic impacts, with the 90% export loss scenario leading to the most substantial producer surplus declines. Gradually easing export restrictions, as seen in the staggered export shock scenario, can mitigate some economic losses ($3,576 million compared to $4,077 million for the 90% export loss scenario). These findings highlight the importance of maintaining export market access, along with implementing biosecurity measures, rapid response protocols, and targeted financial support to mitigate the economic effects of ASF.

Economic evaluations of swine disease have been conducted across a variety of regions, including Europe (Berentsen et al., 1992; Meuwissen et al., 1999; Saatkamp et al., 2000; Vanthemsche, 1994), Africa (Chenais et al., 2017; Mulumba-Mfumu et al., 2019), and Asia (Mason-D'Croz et al., 2020; Nguyen-Thi et al., 2021; Tao et al., 2020; You et al., 2021). However, varying methodologies, diseases, nature of outbreaks, and swine production characteristics limit the external validity of the results, making it difficult to draw general conclusions. Economic evaluations of swine diseases focusing on the United States have been limited. Recently, using the CARD Long-Run Land Use model, Carriquiry et al. (2023) found that an ASF outbreak in the United States could lead to losses averaging $7.5 billion per year. Paarlberg et al. (2009) examined the economic impact of a hypothetical classical swine fever (CSF) outbreak in the United States and projected losses ranging from $2.6 billion to $4.1 billion. Brown et al. (2021) provided a comprehensive review of the known risks, economic losses, and potential transmission pathways of ASF for the United States. Most of these studies consider the impacts from slaughter hogs to consumers, with none emphasizing the effects on agents producing weaners, cull hog traders, and live hog importers. Understanding the full distribution of economic impacts of ASF can better inform the effective allocation of resources for disease prevention and response efforts.

The remainder of the paper is structured as follows. The first section concludes with an overview of the U.S. hog supply chain. The second section details the methodology. The third section describes the nature and sources of the data. The fourth section presents the simulation scenarios followed by results in the fifth section. Finally, the sixth section offers conclusions, policy insights, study limitations, and suggestions for future research.

Overview of the U.S. hog industry

Traditionally, United States hog production consisted of farrow-to-finish operations, feeder pig producers, and feeder pig finishers. However, due to structural changes, the number of farms has declined by over 70% since 1990, leaving fewer but larger and more specialized operations (Christen, 2021; *USDA ERS*, 2023). Today, hog farms are generally categorized into three production types: farrow-to-wean, wean-to-feeder, and feeder-to-finish (Figure 2.1). In the first stage, piglets are raised to about 10-12 pounds before transitioning to the feeder stage, where they are fed various protein rations until they reach 40-60 pounds. Finally, they enter the finishing phase, where they are grown to a slaughter weight of 280 pounds, typically in year-round confined production (*USDA ERS*, 2023).

Most live hogs are processed locally by major packers such as Smithfield Foods, Tyson Foods, JBS Swift, Hormel Foods, Cargill Meat Solutions, and Seaboard. Approximately one-third of pork is sold as fresh meat, with the remainder processed into products like ham, bacon, and sausage, with the loin being the most prized cut (*AgMRC*, 2021). The United States has been a net pork exporter since 1995, consistently ranking among the top five global exporters with an average export share of 32%. Major export markets, including Mexico, Japan, China/Hong Kong, and Canada, account for about 75% of U.S. pork exports. Over the last decade, more than 93% of U.S. pork imports have come from Canada and the EU. Additionally, United States imports live hogs, primarily from Canada, for slaughter and finishing, while a small number of hogs are exported for breeding to Mexico, China, and Canada (*USDA ERS*, 2023).

Another important part of the swine supply chain is the cull hog segment, which mostly comprises of sows and boars selected due to health, market conditions, and repopulation efforts. Culls represent about 6% of the hogs marketed in the United States and are financially significant for both producers and consumers, warranting their inclusion in economic analyses.

Methodology

Multimarket Simulation Model

To capture the economic welfare effects of ASF, we utilize an EDM that characterizes the vertical structure of the U.S. pork supply chain. One advantage of an EDM is its ability to effectively capture all market linkages and the endogeneity of prices and quantities (Wohlgenant, 2005). The basic EDM follows the structure set forth by Muth (1964) and Gardner (1975). EDMs have gained widespread usage in the literature for analyzing the welfare impacts of research, technology adoption, regulation, advertising, and invasive species (e.g., Balagtas & Kim, 2007; Brester et al., 2004; Lemieux & Wohlgenant, 1989; Lusk & Anderson, 2004; Lusk & Norwood, 2012; Pendell et al., 2010; Schroeder & Tonsor, 2011; Sun, 2006; Tonsor & Schroeder, 2015; Wohlgenant, 1993).

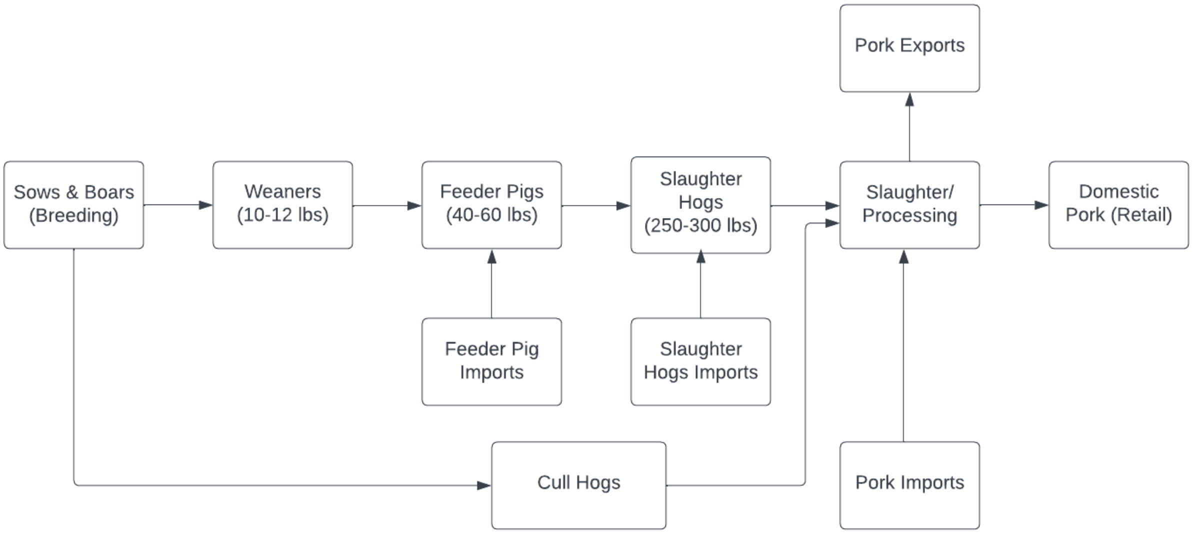

Figure 2.1. Structure of the U.S. swine industry

Figure 2.1 represents the structure of the U.S. swine industry modeled in this study. The EDM comprises the following sectors: 1) sows (breeding), 2) weaners, 3) feeder pigs, 4) slaughter hogs, 5) cull hogs, 6) wholesale, and 7) retail. Important to note here is that retail in this context reflects all end-user products, including both domestic retail (e.g., grocery stores for at-home consumption) and food service (e.g., restaurants for away-from-home consumption). To sufficiently capture international trade, we incorporate the exchange of both pork products and live swine at the appropriate levels (Beach et al., 2007). For simplicity, the structural model omits error terms and the potential substitutability of pork and other meat types at the retail level. In the following series of demand and supply equations which represent our structural model, superscripts r, wh, s, ch, f, w, and is denote retail, wholesale, slaughter hogs, cull hogs, feeder pigs, weaners, and sow market levels, respectively. P is price, Q is quantity; and G and PL are weight per weaner and pigs per liter, respectively. Z and W denote demand and supply shifters, respectively. Subscripts i and e denote imports and exports, respectively. Equations (2.1) – (2.22) omit superscripts for demand and supply, as market-clearing conditions require demand to equal supply.

U.S. Pork Marketing Chain

(2.1) Retail pork primary demand $Q^r = f_1(P^r, Z^r)$

(2.2) Retail pork derived supply $Q^r = f_2(P^r, Q^{wh}, W^r)$

(2.3) Wholesale pork derived demand $Q^{wh} = f_3(P^{wh}, Q^r, Z^{wh})$

(2.4) Wholesale pork derived supply $Q^{wh} = f_4\left(P^{wh}, Q^s, Q^{ch}, Q_i^{wh}, Q_e^{wh}, W^{wh}\right)$

(2.5) Imported wholesale pork derived demand $Q_i^{wh} = f_5\left(P_i^{wh}, Q^{wh}, Z_i^{wh}\right)$

(2.6) Imported wholesale pork derived supply $Q_i^{wh} = f_6\left(P_i^{wh}, W_i^{wh}\right)$

(2.7) Exported wholesale pork derived demand $Q_e^{wh} = f_7(P^{wh}, Z_e^{wh})$

(2.8) Slaughter hog derived demand $Q^s = f_8(P^s, Q^{wh}, Z^s)$

(2.9) Slaughter hog derived supply $Q^s = f_9(P^s, Q^f, Q_i^s, W^s)$

(2.10) Imported slaughter hog derived demand $Q_i^s = f_{10}(P_i^s, Q^s, Z_i^s)$

(2.11) Imported slaughter hog derived supply $Q_i^s = f_{11}(P_i^s, W_i^s)$

(2.12) Cull hog derived demand $Q^{ch} = f_{12}(P^{ch}, Q^{wh}, Z^{ch})$

(2.13) Cull hog derived supply $Q^{ch} = f_{13}(P^{ch}, I^s, W^{ch})$

(2.14) Feeder pig derived demand $Q^f = f_{14}(P^f, Q^s, Z^f)$

(2.15) Feeder pig derived supply $Q^f = f_{15}\left(P^f, Q^w, Q_i^f, W^f\right)$

(2.16) Imported feeder pig derived demand $Q_i^f = f_{16}\left(P_i^f, Q^f, Z_i^f\right)$

(2.17) Imported feeder pig derived supply $Q_i^f = f_{17}\left(P_i^f, W_i^f\right)$

(2.18) Weaner derived demand $Q^w = f_{18}(P^w, Q^f, Z^w)$

(2.19) Weaner derived supply $Q^w = PL \cdot G \cdot I^s \cdot W^w$

(2.20) Weight per weaner $G = f_{20}(P^w, W^g)$

(2.21) Pigs per litre $PL = f_{21}(W^{pl})$

(2.22) Sow inventory $I^s = f_{22}\left(P^w, W^{is}\right)$

Following Wohlgenant (1993), we incorporate variable input proportions by allowing quantities to vary across the marketing levels in the marketing chain. Taking a logarithmic approximation to equations (2.1) – (2.22) and placing all endogenous variables on the left while isolating exogenous shocks on the right side of each equation yields the following EDM:

U.S. Pork Marketing Chain

(2.1') Retail pork primary demand $EQ^r - \eta^r EP^r = EZ^r$

(2.2') Retail pork derived supply $EQ^r - \epsilon^r EP^r - \tau^{whr} EQ^{wh} = EW^r$

(2.3') Wholesale pork derived demand $EQ_{wh} - \eta^{wh} EP^{wh} - \tau^{rwh} EQ^r = EZ^{wh}$

(2.4') Wholesale pork derived supply

$$EQ^{wh} - \epsilon^{wh}EP^{wh} - \tau^{swh}\left(\frac{Q^{s}}{Q^{wh}}\right)EQ^{s} - \tau^{chwh}\left(\frac{Q^{ch}}{Q^{wh}}\right)EQ^{ch} - \left(\frac{Q_i^{wh}}{Q^{wh}}\right)EQ_i^{wh} + \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EQ_e^{wh} = EW^{wh}$$

(2.5') Imported wholesale pork derived demand

$$EQ_i^{wh} - \eta_i^{wh}EP_i^{wh} - \tau^{rwh}EQ^{wh} = \left(\frac{Q_i^{wh}}{Q^{wh}}\right)EZ_e^{wh} + EZ_i^{w}$$

(2.6') Imported wholesale pork derived supply

$$EQ_i^{wh} - \epsilon_i^{wh}EP_i^{wh} = EW_i^{wh}$$

(2.7') Exported wholesale pork derived demand

$$EQ_e^{wh} - \eta_e^{wh}EP^{wh} = EZ_e^{wh}$$

(2.8') Slaughter hog derived demand

$$EQ^{s} - \eta^{s}EP^{s} - \tau^{whs}EQ^{wh} = \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EZ_e^{wh} + EZ^{s}$$

(2.9') Slaughter hog derived supply

$$EQ^{s} - \epsilon^{s}EP^{s} - \tau^{fs}\left(\frac{Q^{f}}{Q^{s}}\right)EQ^{f} - \tau^{whs}\left(\frac{Q_i^{s}}{Q^{s}}\right)EQ_i^{s} = EW^{s}$$

(2.10') Imported slaughter hog derived demand

$$EQ_i^{s} - \eta_i^{s}EP_i^{s} - \tau^{sis}EQ^{s} = \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EZ_e^{wh} + EZ_i^{s}$$

(2.11') Imported slaughter hog derived supply

$$EQ_i^{s} - \epsilon_i^{s}EP_i^{s} = EW_i^{s}$$

(2.12') Cull hog derived demand

$$EQ^{ch} - \eta^{ch}EP^{ch} - \tau^{whch}EQ^{wh} = \left(\frac{Q_e^{hw}}{Q^{wh}}\right)EZ_e^{wh} + EZ^{ch}$$

(2.13') Cull hog derived supply

$$EQ^{ch} - \epsilon^{ch}EP^{ch} - \tau^{sich}EI_s = EW^{ch}$$

(2.14') Feeder pig derived demand

$$EQ^{f} - \eta^{f}EP^{f} - \tau^{sf}EQ^{s} = \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EZ_e^{wh} + EZ^{f}$$

(2.15') Feeder pig derived supply

$$EQ^{f} - \epsilon^{f}EP^{f} - \tau^{wf}\left(\frac{Q^{w}}{Q^{f}}\right)EQ^{w} - \tau^{iff}\left(\frac{Q_i^{f}}{Q^{f}}\right)EQ_i^{f} = EW^{f}$$

(2.16') Imported feeder pig derived demand

$$EQ_i^{f} - \eta_i^{f}EP_i^{f} - \tau^{fif}EQ^{f} = \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EZ_e^{wh} + WZ_i^{f}$$

(2.17') Imported feeder pig derived supply

$$EQ_i^{f} - \epsilon_i^{f}EP_i^{f} = EW_i^{f}$$

(2.18') Weaner derived demand

$$EQ^{w} - \eta^{w}EP^{w} - \tau^{fw}EQ^{f} = \left(\frac{Q_e^{wh}}{Q^{wh}}\right)EZ_e^{wh} + EZ^{w}$$

(2.19') Weaner derived supply

$$EQ^{w} - EPL - EG - EI^{s} = EW^{w}$$

(2.20') Weight per weaner

$$EG - \epsilon^{gpw}EP^{w} = EW^{g}$$

(2.21') Pigs per litre

$$EPL = EW^{pl}$$

(2.22') Sow inventory

$$EI^{s} - \epsilon^{sipw}EP^{w} = EW^{is}$$

where E represent the relative change operator (i.e., $EQ = dlnQ = \frac{\mathrm{dQ}}{Q}$). ϵ^{i}, η^{i}, and τ^{ij} denote supply, demand, and quantity transmission elasticities, respectively. Together with all other parameters, these are fully defined in the appendix section. Following Balagtas and Kim (2007), the EDM can be expressed in a matrix form as:

$$Ay = x \tag{2.23}$$

where A is a matrix of parameters, y is a vector of endogenous variables and x is a vector of exogenous shocks. The system can be solved for proportional changes in endogenous variables given by:

$$y = A^{-1}x \tag{2.24}$$

The resulting proportional changes are used to calculate changes in prices and quantities and changes in producer and consumer welfare. Following Wohlgenant (2011), changes in consumer and producer welfare emanating from ASF shocks be calculated as:

$$\Delta \mathrm{C}S = -P^{r}Q^{r}(EP^{r} - EZ^{r})(1 + 0.5EQ^{r}) \tag{2.25}$$

$$\Delta \mathrm{P}S^{m} = P^{m}Q^{m}(EP^{m} + EW^{m})(1 + 0.5EQ^{m}) \tag{2.26}$$

where CS and PS denote consumer and producer surplus, respectively. For consumer surplus, the superscript r denotes retail level. For producer surplus, the superscript m denotes the market level (i.e., *wh*, *s*, *ch*, *f*, and *w*).

Data for the economic model

Data for economic analysis includes base values, model parameters, and exogenous shocks. Base prices and quantities for hogs and pork were collected from the Livestock Marketing Information Centre (LMIC), with averages from the first quarter of 2022 used as the baseline. These values are summarized in appendix Table A1. To calibrate the EDM, supply, demand, and quantity transmission elasticities were sourced from the literature. In cases where specific elasticities were unavailable, they were estimated using Ordinary Least Squares (OLS) regression. The elasticities used in the model are presented in Tables A2 and A3. Additionally, Table A4 details the production, import, and export shares for swine and pork, which complement the elasticities in calibrating the economic model. These shares were calculated based on the base values.

Exogenous swine supply shocks were estimated as percentage changes from baseline hog quantities, using output from an epidemiological model and insights from past ASF events reported in the literature. Trade shocks were inferred based on the epidemiology of ASF and likely U.S. policy responses in the event of an outbreak. Consumer demand shocks were informed by existing literature.

ASF simulation scenarios

To quantify the economic impacts of ASF, we examine two hypothetical ASF outbreak scenarios: 1) small production outbreak and 2) large production outbreak, both with corresponding trade policy restrictions that limit U.S. exports and potential adverse consumer reactions. Each outbreak scenario evaluates potential ASF-related production shocks resulting from swine death and culling, export restrictions, and domestic pork demand responses due to ASF. The scenarios are presented as follows:

1. *Small Production Outbreak Scenario*

   The production shocks in the small outbreak scenario are derived from an epidemiological model of a hypothetical ASF outbreak in the Midwestern U.S., utilizing the Generalized Epidemic Modeling Framework (GEMF) and a susceptible-exposed-infected-removed (SEIR) compartment approach. The model was primarily built to understand ASF transmission through swine movement networks (see Yang et al. (2023) for more detail). Simulating ASF outbreaks from random farms 10,000 times yielded a median epidemic size of 41,681 swine and a median epidemic duration of 70.32 days. We used the median to avoid the influence of outliers and provide a typical expected outcome for the scenario. By using the quantity of hogs for each production type in Iowa, and their proportion of U.S. swine quantities in the first quarter of 2022, we translated the epidemic size into the small outbreak production shock shown in Table 2.1. It is important to note that Iowa and much of the Midwest have a smaller proportion of sow farrowing operations, so the model may understate the impacts that would occur in regions where farrowing is more prevalent and critical to production recovery. It is important to note that Iowa and much of the Midwest have a smaller proportion of sow farrowing operations, so the model may understate the impacts that would occur in regions where farrowing is more prevalent and critical to production recovery. Since the median epidemic duration is less than one quarter, we assume that the small outbreak will not extend beyond the affected quarter.

In the small ASF outbreak scenario, we consider trade restrictions resulting in a 20% decrease in U.S. pork exports. As ASF is a notifiable disease with the WOAH, the United States faces decreased export risks for two main reasons: adherence to WOAH's export restriction guidelines during outbreaks and trade restrictions imposed by importing nations to protect their domestic pork industries. Historical instances show countries face strict trade restrictions upon ASF detection; for example, in 2023, Armenia, Australia, Japan, the Philippines, Taiwan, and Ukraine ceased all pork imports from Sweden following its first ASF case in wild boar.

However, the United States' significance as a global pork supplier may mitigate potential negative trade responses, given prospects of regionalization to maintain trade from disease-free areas and the potential for quick trade resumption if mitigation efforts succeed. Given the small, contained, and short-lived nature of the hypothetical Iowa outbreak in this analysis, export regionalization is possible. Iowa, accounting for about a third of all U.S. pork exports in 2021, underpins a scenario where a 20% export loss occurs, assuming the rest of the U.S. can continue exporting pork and trade restrictions may be short-lived.

Regarding potential consumer adverse reactions, existing research shows varied impacts on meat demand. Wang et al. (2024) found that while BSE reduced beef consumption by 1.24% in 2003 to 1.20% in 2006, HPAI had no contemporaneous effects on meat consumption. Lee et al. (2022) found that U.S. consumer reactions are inversely related to prior knowledge about ASF, but consumers are generally unaware of the disease. Thus, for this small outbreak scenario, we assume negligible consumer reactions, implying no change in consumer demand.

2. *Large Production Outbreak Scenario*

To develop a plausible hypothetical scenario for a large outbreak, we relied on insights from the first ASF outbreak in China, which occurred over roughly four quarters from August 2018 to July 2019, and was one of the most severe in history (Wang et al., 2024). Using data for swine losses from the Chinese outbreak as reported by You et al. (2021), we estimate the distribution of the losses across the four quarters[1] if the outbreak

---

[1] For the purposes of this estimation, the first quarter refers to the first 3 months of the outbreak, second quarter refers to the 4th – 6th months, and so forth.

were to occur in the United States. Our analysis assumes a 7.33% reduction in U.S. hog and pork production across the four quarters, as presented in Table 2.1. The analysis shows that out of the 7.33% total production losses, 3% occurred in the first quarter, 3% in the second quarter, 1% in the third quarter, and 0.33% in the fourth quarter. Applying these proportions to the 2022 U.S. hog inventory data, we calculate the corresponding supply shocks for each production type across the four quarters that are used in the EDM. These quarterly shocks are presented in Table 2.2 and are of a similar magnitude as Paarlberg et al. (2009) who found an 8.3% decline in the U.S. hog quantities following a hypothetical Classical Swine Fever (CSF) outbreak. Additionally, the widespread outbreak would likely lead to a decrease in domestic demand due to increased consumer awareness. Consistent with Paarlberg et al. (2009), we assumed a 1% fall in consumer demand across the four quarters. For the large outbreak scenario, three export response scenarios were simulated: (i) a 60% reduction in U.S. pork exports due to anticipated stricter policies in the event of a large-scale ASF outbreak, (ii) a worst case scenario of 90% export loss, and (iii) a situation where export restrictions relax as the outbreak wanes across the four quarters (i.e., 90% loss in Q1, 75% loss in Q2, 60% in loss Q3, and 45% loss in Q4) (Table 2.1).

Table 2.1. Proportionate change in swine and pork production, exports, and domestic demand from hypothetical ASF outbreaks

	Small Outbreak	Large Outbreak		
		(i)	(ii)	(iii)
Production	-0.00044	-0.0733	-0.0733	-0.0733
Exports	-0.20	-0.60	-0.90	_[b]
Demand	0	0.01	0.01	0.01

[b] *Export restrictions lessen as the outbreak subsides (i.e., the size of the shock by quarter are -0.90, -0.75, -0.60, and -0.45).*

Table 2.2. Logarithmic reductions in U.S. swine production due to hypothetical ASF outbreaks

		Supply Shock	
Quarter	Swine Type	Small Outbreak	Large Outbreak
1	Sow	0.00001	0.00092
	Weaner	0.00015	0.00980
	Feeder	0.00014	0.00960
	Slaughter Hog	0.00013	0.00941
	Cull Hogs	0.00000	0.00027
2	Sow		0.00092
	Weaner		0.00980
	Feeder		0.00960
	Slaughter Hog		0.00942
	Cull Hogs		0.00026
3	Sow		0.00030
	Weaner		0.00327
	Feeder		0.00320
	Slaughter Hog		0.00314
	Cull Hogs		0.00008
4	Sow		0.00010
	Weaner		0.00108
	Feeder		0.00106
	Slaughter Hog		0.00104
	Cull Hogs		0.00003

Small production outbreak scenario shocks are based on a hypothetical ASF outbreak in Iowa. Large outbreak shocks are calibrated based on the Chinese ASF 2018/2019 outbreak. U.S. swine inventories data for the year 2022 were used for both scenarios.

Results

The results of the study are presented below. We outline the economic welfare impacts of hypothetical ASF outbreaks across different scenarios, including small and large production shocks, with varying levels of export restrictions and consumer demand responses.

Small Production Outbreak Scenario

Table 2.3 presents a summary of percentage changes in pork prices and quantities, derived using equations (2.1) - (2.22), resulting from a 0.044% loss in swine production and a 20% loss in exports. The changes are intuitive and theoretically consistent with the introduction of negative supply shocks from sow to the market hog levels. Weaner, feeder pig, cull hog, and slaughter hog prices and quantities all decline, along with sow quantities. The negative supply shocks shift supply at all affected levels (i.e., sow to slaughter hogs) leftward, resulting in a decrease in derived demand and prices at each preceding level. Similarly, the quantity and prices of imported feeder pigs and imported slaughter hogs also decline. Initially, the decrease in quantities from weaners to market hogs reduces wholesale and retail pork supply. However, this is offset by the reduced pork exports, which increases pork quantities at the wholesale and retail levels and reduces prices.

Table 2.3. Percentage changes in endogenous variables for the small ASF outbreak scenario

Endogenous Variables	Price	Quantity
Retail pork	-0.04	0.03
Wholesale pork	-0.01	0.03
Imported wholesale pork	-0.63	-0.89
Exported wholesale pork	_[a]	-19.99
Slaughter hogs	-0.16	-2.03
Imported Slaughter hogs	-3.76	-0.76
Cull hogs	-1.62	-0.99
Feeder pigs	-4.56	-2.92
Imported feeder pigs	-0.99	-0.99
Weaners	-6.74	-0.68
Sows	-	-0.61

Note: Percentage changes are based upon average 2022 Q1 prices and quantities for swine and pork. [a]*Export prices are assumed to be equal to domestic prices.*

Using equations (2.25) and (2.26), we calculate the economic welfare impacts of a hypothetical small ASF outbreak scenario. Table 2.4 presents the consumer and producer welfare impacts. The outbreak results in significant economic welfare impacts, primarily affecting producer surplus negatively while providing some benefits to consumers. The total pork industry producer surplus declines by approximately $285.90 million. Slaughter hog and cull hog segments see declines of $8.92 million and $2.47 million, respectively, while wholesale pork experiences a smaller loss of $1.54 million. For most producers, from weaners to slaughter hogs, reductions in producer surplus are driven by decreased prices and quantities. Although quantities increase at the wholesale and retail levels, the decrease in prices results in welfare loss at these levels. Conversely, the consumer surplus for retail pork increases by $8.31 million due to lower retail pork prices and increased quantities at the retail level, stemming from the decreased export demand. Consumers benefit from the lower prices and increased availability of pork products.

Table 2.4. Producer and consumer changes from a hypothetical ASF small outbreak

Surplus Measure	Million Dollars
Producer Surplus	
Retail pork	-8.31
Wholesale pork	-1.54
Slaughter hog	-8.92
Cull hog	-2.47
Feeder pig	-126.80
Weaner	-137.87
Total Pork Industry Producer Surplus	*-285.90*
Consumer surplus	
Retail pork	8.31

[a] *We assume a 20% export loss and 0 % loss in retail demand.*

Large Production Outbreak Scenario

60% Export Loss and 1% Consumer Demand Shock

Table 2.5 presents the results of the large production outbreak scenario characterized by a 60% export loss and 1% demand shock. Over the four quarters, the outbreak leads to substantial welfare losses, with the producer surplus experiencing considerable fluctuations. The total pork industry producer surplus declines each quarter, with the most significant losses in Q3 and Q4, amounting to $566.65 million and $628.90 million, respectively. While the production, consumer demand, and export shocks are similar in Q1 and Q2, observed welfare differences are mostly explained by differences in base prices and quantities. For the first two quarters, retailers and wholesalers experienced positive welfare gains largely explained by increases in prices (Table A5). The feeder pig and weaner segments are particularly hard-hit, similar to the small outbreak scenario, but with higher losses. Retail pork initially benefits in the first two quarters but reverses to significant losses in the latter half. Although consumer surplus remains negative throughout, it shows consistent improvement from Q1 to Q4. This trend can be attributed to the gradual waning of the outbreak over these quarters, coupled with a sustained 60% reduction in exports. Consequently, the domestic market experiences improved quantities and lower prices in Q3 and Q4, leading to the observed improvements in consumer surplus. The same logic explains the drastic fall in retail and wholesale producer surplus in both quarters. In contrast, the small outbreak scenario showed a gain in consumer surplus ($8.31 million) due to lower retail prices and increased pork quantities, highlighting the more severe impact of a large-scale ASF outbreak on consumer welfare.

Table 2.5. Producer and consumer changes from a hypothetical ASF large outbreak (60% Export Loss Scenario, $ millions)[a]

	Million Dollars			
Surplus Measure	**Q1**	**Q2**	**Q3**	**Q4**
Producer Surplus				
Retail pork	426.65	425.44	-24.93	-174.98
Wholesale pork	89.66	87.79	6.18	-20.69
Slaughter hog	-37.23	-33.89	-30.21	-27.75
Cull hog	-11.67	-10.18	-6.78	-5.46
Feeder pig	-432.89	-357.63	-269.00	-219.81
Weaner	-474.60	-355.42	-241.90	-180.21
Total Pork Industry Producer Surplus	*-440.07*	*-243.89*	*-566.65*	*-628.90*
Consumer surplus				
Retail pork	-633.70	-631.77	-182.18	-30.48

Base prices and quantities are for 2022. Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] *We assume a 60% export loss and 1% loss in retail demand.*

90% Export Loss and 1 % Consumer Demand Shock

In this scenario, welfare effects follow a similar pattern to the 60% export loss scenario, but with greater magnitudes. Over the four quarters, the total producer surplus in the pork industry declines, peaking at a loss of $860.09 million in Q1 (Table 2.6). Retail pork shows initial gains in Q1 ($399.68 million) and Q2 ($398.41 million), turning negative in Q3 ($52.06 million) and Q4 ($201.74 million). Wholesale pork also follows this trend, with gains in Q1 ($84.71 million) and Q2 ($83.00 million), followed by minor gains in Q3 ($1.34 million) and losses in Q4 ($25.57 million). This trend mirrors the 60% export loss scenario but with more pronounced negative losses in Q4.

The feeder pig and weaner segments face the most severe negative surplus changes, indicating significant economic losses, much like the previous scenarios but with even larger losses. Consumer surplus remains consistently negative across all quarters, with the most substantial losses recorded in Q1 ($606.83 million) and Q2 ($604.75 million). With similar production and consumer demand shocks, two key differences stand out: total consumer welfare loss is less pronounced in the 90% export scenario compared to the 60% scenario, while producers incur greater losses under the 90% scenario. This indicates that producers are more adversely affected by export market losses than consumers. Overall, the net welfare loss is higher under the 90% export loss scenario.

Table 2.6. Producer and consumer changes from a hypothetical ASF large outbreak (90% Export Loss Scenario, $ millions)[a]

	Million Dollars			
Surplus Measure	**Q1**	**Q2**	**Q3**	**Q4**
Producer Surplus				
Retail pork	399.68	398.41	-52.06	-201.74
Wholesale pork	84.71	83.00	1.34	-25.57
Slaughter hog	-49.32	-43.31	-37.56	-33.41
Cull hog	-15.06	-12.55	-8.57	-6.82
Feeder pig	-606.28	-460.61	-328.87	-250.32
Weaner	-673.82	-434.60	-262.77	-171.10
Total Pork Industry Producer Surplus	*-860.09*	*-469.65*	*-688.49*	*-688.96*
Consumer surplus				
Retail pork	-606.83	-604.75	-154.98	-3.54

Base prices and quantities are for 2022. Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] We assume a 90% export loss and 1% loss in retail demand

Staggered Export Shocks

The third large ASF production outbreak scenario involves staggered export shock across four quarters, starting with a 90% export loss in Q1, reducing to 75% in Q2, 60% in Q3, and 45% in Q4, combined with a 1% decline in consumer demand in each of the four quarters. This scenario assumes that export restrictions lessen as the outbreak improves and the welfare impacts are presented in Table 2.7.

The total pork industry producer surplus experiences considerable fluctuations, with the largest loss recorded in Q1 at $860.09 million. Retail pork initially shows positive gains in Q1

($399.69 million) and Q2 ($411.84 million), but turns negative in Q3 ($24.91 million) and Q4 ($161.38 million). This pattern is consistent with the other large scenarios but shows a less drastic negative impact in the latter quarters. Wholesale pork follows a similar trend, with positive surplus changes in Q1 and Q2 ($84.71 million and $85.43 million, respectively), minor gains in Q3 ($6.18 million), and a small loss in Q4 ($18.30 million). The feeder pig and weaner segments face significant negative surplus changes, although less severe than in the 90% export loss scenario. Consumer surplus for retail pork consistently declines across all quarters, with the most substantial losses recorded in Q1 ($606.83 million) and Q2 ($618.14 million). This decline is slightly more severe compared to the 90% export loss scenario. This scenario demonstrates the importance of maintaining market access to mitigate producer surplus losses, although it is less favorable to consumers as export restrictions ease.

Table 2.7. Producer and consumer changes from a hypothetical ASF large outbreak (Staggered Export Loss Scenario, $ millions)[a]

	Million Dollars			
Surplus Measure	**Q1**	**Q2**	**Q3**	**Q4**
Producer Surplus				
Retail pork	399.68	411.84	-24.91	-161.38
Wholesale pork	84.71	85.43	6.18	-18.30
Slaughter hog	-49.32	-38.04	-28.64	-21.73
Cull hog	-15.06	-11.14	-6.33	-3.98
Feeder pig	-606.28	-395.27	-237.34	-147.99
Weaner	-673.82	-370.52	-193.82	-109.36
Total Pork Industry Producer Surplus	*-860.09*	*-317.70*	*-484.85*	*-462.74*
Consumer surplus				
Retail pork	-606.83	-618.14	-182.07	-43.90

Base prices and quantities are for 2022. Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] *We assume a 90% export loss in Q1, 75% in Q2, 60% in Q3, and 45% in Q4 and 1% loss in retail demand across all four quarters.*

Overall, our analysis across all scenarios shows potential net welfare losses ranging from $277 million to $4,077 million over four quarters. At the upper end, this represents a significant financial impact, amounting to approximately 6.5% of the pork industry's $62 billion contribution to value added in 2023. These losses are comparable, though somewhat lower, than the $7.5 billion in annual losses estimated by Carriquiry et al. (2023) using the CARD model. The difference likely stems from their assumption of prolonged, complete export market closures and a more extended outbreak period.

Similarly, Kashyap et al. (2024) projects welfare losses of up to $55.46 billion in the event of an ASF incursion. Their study focuses solely on the pork market and assumes a more substantial reduction in consumer demand—up to 32%—whereas our model considers a much smaller 1% demand shock. This marked disparity in demand reduction assumptions likely explains the difference in projected welfare losses.

In a study on Classical Swine Fever (CSF), Paarlberg et al. (2009) estimated losses between $2.6 billion and $4.1 billion over 20 quarters. While both their production and demand shocks are comparable to our large production outbreak scenario, discrepancies in welfare losses can be explained by differences in outbreak duration and grower expectations incorporated in their model. For example, the same production losses are spread over 20 quarters in their model, whereas they are spread over just four quarters in our model. Additionally, grower expectations in their model play a key role in the price recovery trajectory, with adjusted expectations leading to quicker recovery in hog prices and lower welfare losses in later quarters.

Conclusion

The incursion of African Swine Fever (ASF) can have substantial welfare effects on the U.S. hog supply chain, necessitating an understanding of its potential economic consequences to inform prevention and support efforts. Our analysis, incorporating various outbreak scenarios, highlights the varying degrees of impact on different segments of the U.S. pork supply chain.

Our analysis sheds light on how outbreak severity and market response interact to dictate the costs of ASF. For small outbreaks confined to a single state like Iowa, the impact is relatively contained but still notable. The total pork industry producer surplus declines by approximately $285.90 million, primarily driven by losses in the weaner and feeder pig segments. The consumer surplus, however, increases slightly by $8.31 million due to lower retail pork prices and increased availability.

In contrast, large outbreak scenarios depict much more severe economic impacts across the swine supply chain. Analyzing different scenarios, including 60% and 90% export losses, as well as staggered export shocks, provides key insights into the nature of these impacts. Larger export shocks result in more severe welfare losses, with the 90% export loss scenario leading to the most substantial producer surplus declines. It emphasizes the importance of maintaining export market access and the potential benefits of diversifying export destinations to mitigate disease risks. Gradually gaining foreign market access can mitigate some producer losses.

The results underscore several important policy implications. Implementing comprehensive biosecurity measures and rapid response protocols is essential to contain outbreaks quickly and minimize their impacts. Enhanced surveillance and early detection can prevent large-scale outbreaks and reduce economic losses. Given the significant welfare losses experienced by producers, particularly in the feeder pig and weaner segments, targeted financial support and compensation mechanisms are necessary to assist affected producers. This could include subsidies, low-interest loans, or insurance schemes to help producers recover from disease shocks. Ensuring stable pork prices and availability for consumers during outbreaks are vital. Policies aimed at stabilizing the domestic market, such as strategic reserves or import adjustments, can help maintain consumer welfare during crises. Also, it is important to put in place communication plans to help calm domestic consumers to avoid adverse consumer reactions.

A few caveats exist in our analysis. First, our model did not incorporate swine production lags. Due to these lags, prices and quantities do not adjust instantaneously to shocks, meaning that the immediate impacts we observed might evolve differently over time. Also, the costs associated with the disease are likely to persist longer than the four quarters captured in our static analysis, potentially leading to more prolonged economic impacts. Second, our model did not account for substitutability between pork and other meat products at the retail level. This omission can potentially bias our welfare estimates by overlooking consumers' ability to switch to other meat types when pork prices rise, thus overstating consumer welfare loss and understating producer welfare loss. Future studies can benefit from including these to have more comprehensive welfare estimates.

Chapter 3 - How important are trade agreements during poultry disease events?

Introduction

In recent decades, the global poultry industry has witnessed significant growth, becoming a crucial component of international trade in agricultural products. Currently, poultry is the most traded livestock commodity globally. In 2021, global imports of poultry reached nearly 14.2 million metric tons, with imports projected to grow to 17.5 million metric tons by 2031 (Miller et al., 2022). Between 2018 and 2022, Brazil and the United States were the top exporters, accounting for over 56% of global chicken meat exports (Dohlman et al., 2022; Farris et al., 2024; Miller et al., 2022). Nevertheless, this burgeoning trade is often volatile due to a plethora of economic, political, and biological factors. A growing concern is the impact of contagious poultry diseases like Highly Pathogenic Avian Influenza (HPAI) and Newcastle Disease (ND) on global trade volumes and patterns. These diseases not only threaten animal health, but also pose profound economic risks to countries deeply involved in poultry trade (Thompson et al., 2020). For example, in 2022, Asia imported more than 3.4 million metric tons of chicken meat, highlighting the potential impact of trade disruptions (Farris et al., 2024). In the face of such challenges, trade agreements (TAs) between countries can serve as crucial frameworks to mitigate the adverse effects of disease outbreaks on trade flows. By fostering deeper integration among members, TAs are believed to help liberalize non-tariff barriers and facilitate the implementation of Sanitary and Phytosanitary (SPS) measures (Çakır et al., 2018; Grant & Lambert, 2008). Yet, the role of these TAs during contagious animal diseases remains unexplored. This study contributes to filling this gap by assessing the role of TAs in international poultry trade during HPAI and ND outbreaks, highlighting how commitments within TAs may help countries manage disease outbreaks through institutional cooperation.

Historic disease events such as Bovine Spongiform Encephalopathy in the European Union (EU), Canada, and the United States, HPAI in Asia, Canada, EU, and the United States, and Foot and Mouth Disease (FMD) in Taiwan, Brazil, Japan, and Korea have highlighted the fragility of global trade networks in the face of biological threats (Dobrowolska & Brown, 2016; Knowles et al., 2005; Marsh et al., 2005; Ramos et al., 2017; Saatkamp et al., 2000). These disease events often led to international trade restrictions including complete export bans (Bastola, 2015). For example, following the 2014-2015 HPAI outbreak in the United States, over 50 countries-imposed restrictions on U.S. poultry products. Major importers such as China, South Korea, Canada, and Mexico enacted either partial or total bans on U.S. poultry imports, leading to significant declines in U.S. poultry export revenues. This resulted in significant declines in U.S. poultry export income. Broiler exports saw the most significant reduction, with a decrease of $1.1 billion in 2015 from the previous year, representing a 26% drop (Ramos et al., 2017).

During animal disease events, the World Trade Organization (WTO), supported by numerous bilateral and multilateral trade agreements, plays a pivotal role in balancing disease containment with minimal disruptions to global trade (Grant & Lambert, 2008; Marsh et al., 2005). In order to safeguard human, animal, and plant health from the risks posed by invasive species introduced through international trade, the WTO’s Agreement on the Application of SPS measures delineates guidelines for the control, inspection, and certification of imports. When construed in conjunction with the Agreement on Technical Barriers to Trade, the SPS Agreement aims to facilitate the uniform application of these sanitary and phytosanitary measures, concurrently avoiding covert forms of protectionism. While member countries are encouraged to use international standards, the agreement allows them to set their own standards as long as they are based on science and can even adopt higher levels of protectionism when necessary.

Given these circumstances, understanding the performance of TAs under adverse events becomes paramount. It provides insights into the stability and resilience of international trade networks and how trade policies can be adapted to protect public health without unnecessarily hindering trade. The role of TAs in facilitating market access and trade flows is well-documented (Baier & Bergstrand, 2007; Gharleghi & Shafighi, 2020; Grant & Lambert, 2008; Krueger, 1997). The general consensus is that TAs promote deeper integration by reducing non-tariff barriers, including technical standards, food safety concerns, and domestic regulations (Grant & Lambert, 2008). Article XXIV of the General Agreement on Tariffs and Trade (GATT) stipulates that members must eliminate barriers on nearly all trade within a TA. Similarly, the impact of invasive species, including animal diseases, on trade has been extensively researched (Blayney et al., 2006; Cartín-Rojas, 2012; Junker et al., 2009; Morgan & Prakash, 2006; Thompson, 2018; Thompson et al., 2020; Webb et al., 2018). However, these two issues (i.e., TAs and animal diseases) have not been jointly evaluated. Anecdotal evidence suggests that HPAI-related export restrictions on the United States are less severe when a trade agreement exists between the United States and the importing country. Table 3.1 presents the export values, duration, and extent of trade restrictions imposed by the U.S.'s top ten poultry importers following the 2014/2015 HPAI outbreak. Notably, Mexico, Canada, and Guatemala, which have TAs with the United States, enforced shorter restrictions. In contrast, China, Russia, and South Korea imposed the longest bans. While these differences cannot be entirely attributed to trade agreements, their importance is evident.

Table 3.1. Exports and trade restrictions for U.S.'s top ten poultry importers

Country	Exports as of 2014 ($ millions)	Date of effect	Date of lifting	Extent of restrictions
Mexico	1,282	January 2015	August 2015	Regional
Canada	589	January 2015	July 2015	Regional
Hong Kong	521	December 2014	May 2015	Regional
China	315	January 2015	November 2019	Total
Angola	264	January 2015	September 2015	Total
Russia	150	December 2014	February 2017	Total
Cuba	148	August 2014	September 2014	Regional
Taiwan	143	December 2014	November 2015	Regional
South Korea	113	December 2014	August 2016	Total
Guatemala	104	March 2015	August 2015	State

Adapted from Greene (2015). Update on the HPAI Outbreak of 2014-2015, Congressional Research Service. Supplemented with information from USDA's Foreign Agricultural Service, USA Poultry and Egg Export Council and other online sources.

The current study builds on previous related studies in several ways. Thompson et al. (2020) evaluated the effects of HPAI disease events on international trade of poultry products. The authors found that quantity traded, and product type demanded during a disease event differs by commodity. Bastola (2015), using a structural gravity framework while controlling for TAs, revealed the negative effects of FMD on livestock trade. While most studies control for bilateral factors, none have evaluated how TAs influence exports during an animal health crisis. Çakır et al. (2018) conducted a partial equilibrium analysis and found that export losses to United States turkey producers during the 2014/2015 HPAI outbreak were $207 million, and the losses could have been worse had it not been for the loss mitigating effects of TAs. In their study, they conjectured that TAs facilitate confidence building and trust among U.S. trading partners which smoothens implementation of SPS measures.

We employ panel gravity models using an exhaustive dataset of 212 countries and territories involved in poultry trade to investigate the impact of TAs on trade flows during HPAI and ND events. We primarily rely on the Hausman-Taylor (HT) estimator, which enables us to address the endogeneity of our variables while also identifying time-invariant regressors. Using aggregate poultry data, we find that TA members have less bilateral trade during HPAI events than non-TA counterparts, but they have more trade during ND events. Product-specific analysis revealed a generally negative role of TAs during HPAI, consistent with aggregate findings, but indicate mitigated trade effects for the most traded products like frozen chicken parts and cooked chicken during both HPAI and ND events. We also find that TA members experience a quicker rebound in trade, especially during HPAI events. These results highlight the potential of TAs to sustain trade and open markets faster under conditions of animal disease outbreaks.

To effectively manage the impacts of poultry disease outbreaks, it is crucial to enhance coordination and harmonization of SPS standards within TAs. These standards must be robust enough to handle health crises like HPAI. This requires developing specific protocols for disease outbreaks, regularly updating these standards, and conducting joint training sessions for SPS officials from member countries. Additionally, implementing disease-specific trade protocols within TAs is critical. For HPAI, this might include stricter quarantine measures and more rigorous inspections, while ND protocols could focus on maintaining trade flows with appropriate safeguards. Broadly adopting strategies like regionalization can help mitigate the severity of trade restrictions under HPAI, making them more targeted and less disruptive, especially within TAs.

The remainder of this paper is organized as follows. Section 2 describes the gravity theory that informs our estimation strategy and choice of regressors. Section 3 lays out the hypotheses and the associated estimating equations. Section 4 describes the data. Section 5 presents the results and section 6 concludes with policy implications and caveats to our findings.

Gravity Framework

The gravity model remains the workhorse for analyzing trade policies. Our log-linear gravity specification inspired by Tinbergen's (1962) work is given by:

$$\text{(3.1)} \qquad \ln X_{ij,t} = \lambda_{i,t} + \psi_{j,t} + \beta_2 TA_{ij,t} + \beta_3 ln\phi_{ij} + \varepsilon_{ij,t}.$$

Here, $X_{ij,t}$ is the value of trade from exporter i to importer j at time t, $\lambda_{i,t}$ and $\psi_{j,t}$ are importer-time and exporter-time fixed effects, respectively. $TA_{ij,t}$ is a binary variable indicating the presence of a TA between countries i and j in time period t, and ϕ_{ij} captures trade costs, indicating the ease of market access between the trading partners. The βs are parameters to be estimated and $\varepsilon_{ij,t}$ represents an error term. The importer-time and exporter-time fixed effects effectively control for multilateral resistance and simultaneously accounts for economic sizes. Multilateral resistance is the idea that trade between any two countries is influenced not just by their economic sizes and direct trade costs, but also by their trade engagements with the wider global community. This concept reflects the impact of third-country effects on bilateral trade. Baldwin & Taglioni (2006) highlight the importance of controlling for multilateral resistance, labeling the failure to do so as the gold medal mistake, leading to biased trade flow estimates due to unaddressed correlations with trade costs.

Hypotheses and Estimating Equations

In this section, we present two hypotheses along with the econometric models used to test them. The null hypotheses are founded on the underlying assumption that, by enabling coordination and rapport among trading partners, TAs enhance the immediate application of SPS measures, effectively preventing the imposition of unwarranted trade barriers and aiding in trade recovery. For illustration, let $D_{i,t}$ represent the disease indicator, implying the presence of a disease in an exporting country at time t. The coefficient of the interaction term between $TA_{ij,t}$ and the disease indicator can be denoted as $\beta_{TA_t * D_t}$. Accordingly, the first alternative hypothesis is formulated as:

H_1: $\beta_{TA_t * D_t} > 0$. *During poultry disease events, members of TAs experience less severe negative trade effects compared to non-TA members.*

TAs might provide a protective mechanism for trade during disease outbreaks including specific provisions that affect how member countries respond to poultry diseases. To test H₁, equation (3.1) is modified as follows:

$$(3.2) \qquad lnX_{ij,t} = \lambda_{it} + \psi_{jt} + \beta_1 TA_{ij,t} + \beta_2 HPAI_{i,t} + \beta_3 TA_{ij,t} * HPAI_{i,t} + \beta_4 ND_{i,t} + \beta_5 TA_{ij,t} * ND_{i,t} + \beta_6 ln\phi_{ij} + \varepsilon_{ij,t}$$

where $HPAI_{i,t}$ and $ND_{i,t}$ are indicator variables for the presence of HPAI and ND in exporter i at time t. For simplicity, $HPAI_{i,t}$ and $ND_{i,t}$ may be collectively represented as a disease dummy $D_{i,t}$ as shown in H_1. In the case of equation (3.2), β_3 and β_5 (illustrated as $\beta_{TA_t * D_t}$ in the alternative hypothesis) are the parameters of interest to measure the role of TAs during HPAI and ND events, respectively. All other variables are as previously defined.

Estimating the impact of trade policies within gravity models often faces the challenge of endogeneity, particularly with trade policy variables such as TAs (Larch & Yotov, 2023; Yotov et al., 2016). This endogeneity arises due to omitted variables that affect both bilateral trade flows and the likelihood of TA formation. This omission risks attributing trade enhancement solely to TAs without accounting for other contributing characteristics of trading partners. Country-pair fixed effects have emerged as a preferred solution to address the endogeneity of trade policy variables (Agnosteva et al., 2014; Baier & Bergstrand, 2007; Egger & Nigai, 2015; Larch & Yotov, 2023). These fixed effects absorb all time-invariant gravity covariates, including bilateral trade costs (ϕ_{ij}), while still allowing for the identification of TAs and disease indicators, which vary over time. Applied to our setting, we adopt the following specification:

$$lnX_{ij,t} = \lambda_{it} + \psi_{jt} + \pi_{ij} + \beta_1 TA_{ij,t} + \beta_2 HPAI_{i,t} + \beta_3 TA_{ij,t} HPAI_{i,t} + \beta_4 ND_{i,t} + \beta_5 TA_{ij,t} ND_{i,t} + \varepsilon_{ij,t} \tag{3.3}$$

While the specification outlined in equation (3.3) addresses the endogeneity of TA, it complicates the identification of the disease indicators. Specifically, when considering $HPAI_{i,t}$ and $ND_{i,t}$, which varies by exporter and time, their effect is subsumed by the exporter-time fixed effects making identification challenging. In the existing literature, some approaches have been proposed. One involves the two stage gravity estimation procedure in which the dependent variable is augmented by both domestic and international trade data (Beverelli et al., 2018). Unfortunately, our study lacks access to domestic poultry trade data, rendering this approach unfeasible. An alternative solution is to exclude the fixed effects, re-introduce size and dyadic (bilateral control) variables and use the random (REM) or fixed effects (FEM) approach. The choice between these approaches depends on the correlation between regressors and the error term. Empirical scenarios often lie between the extremes of these two approaches, prompting the exploration of a hybrid estimator.

We adopt the Hauman Taylor (HT) approach to test for H_1. The HT estimator is a consistent and efficient hybrid of the FEM and REM, using instrumental variable (IV) regression techniques. It allows us to address the endogeneity of our regressors while at the same time identifying time-invariant variables. The HT model divides time-varying variables into two subsets $Y_{it} = [Y1_{i,t}, Y2_{i,t}]$ where $Y1_i$ are exogenous and $Y2_{i,t}$ are endogenous. Time-invariant variables are also classified in a similar way (i.e., $Z_{it} = [Z1_i, Z2_i]$). Categorizing our variables in equation (3.3) following the HT criteria yield the following augmented HT model:

(3.4) $$X_{ij,t} = \alpha + \beta'_1 Y1_{i,t} + \beta'_2 Y2_{i,t} + \sigma'_1 Z1_i + \sigma'_2 Z2_i + \mu_i + \varepsilon_{i,t}$$

The complete list of control variables that complement the regressors in equation (3.4) is provided the appendix, specifically in Table B2. In equation (3.4), μ_i represents the unobserved individual-specific effects and $\varepsilon_{i,t}$ constitutes the residual error component. Both are assumed to have zero mean, finite variance and to be independently and identically distributed (i.i.d.) across panels, denoted as i.i.d. (0, σ_μ^2) and i.i.d. (0, σ_ϵ^2). Since $Y2_{i,t}$ and $Z2_i$ are correlated to μ_i, the REM is not consistent for parameters in equation (3.4). On the other hand, the FEM eliminates μ_i by mean differencing the data before estimating β_1 and β_2. While FEM is consistent for these parameters, it also eliminates $Z1_i$ and $Z2_i$ in the process making it unable to estimate σ_1 and σ_2.

The HT estimator derives appropriate instruments through internal data transformations of the model variables. Deviations from the means of $Y1_{i,t}$ and $Y2_{i,t}$ serve as instruments for $Y1_{i,t}$ and $Y2_{i,t}$, $Z1_i$ serve as their own instruments and group of means of $Y1_{i,t}$ are used as instruments for the time invariant $Z2_i$. Intuitively, the FEM and REM can be viewed as special cases of the HT estimator. When all regressors are endogenous, the HT collapses to FEM, and when all regressors are exogenous, the HT reduces to REM.

Understanding coefficients in H_1

In this section, we detail the derivation and interpretation of the interaction coefficient in H_1, as well as its components. Using equation (3.3) and for either disease indicator, $D_{i,t}$, the marginal trade effect of a disease event is captured by the following expression:

$$\frac{\partial lnX_{ij,t}}{\partial D_{i,t}} = \beta_{D_t} + \beta_{TA_t * D_t} TA_{i,j,t} \tag{3.5}$$

where β_{D_t} is the coefficient of $D_{i,t}$ and measures the direct impact of a disease event on the value of trade and $\beta_{TA_t * D_t}$ is the coefficient of the interaction between $D_{i,t}$ and $TA_{i,j,t}$ and it captures the incremental effect that TA membership has on the trade value in the presence of a disease, over and beyond the effect of the disease itself. Equation (3.5) shows that the effect of a disease on the value of trade depends on whether a TA exist on not. The impact of the disease on bilateral poultry trade when trading pairs are not part of a TA (i.e., $TA_{i,j,t} = 0$) is given by:

$$\frac{\partial lnX_{ij,t}}{\partial D_{i,t}} = \beta_{D_t} + \beta_{TA_t * D_t}(0) = \beta_{D_t}. \tag{3.6}$$

When trading pairs are bound by a TA (i.e., $TA_{i,j,t} = 1$), the impact of the disease is given by:

$$\frac{\partial lnX_{ij,t}}{\partial D_{i,t}} = \beta_{D_t} + \beta_{TA_t * D_t}(1) = \beta_{D_t} + \beta_{TA_t * D_t}. \tag{3.7}$$

Therefore, subtracting the effect of the disease on trade without a TA from the effect with a TA results in $\beta_{TA_t * D_t}$. As previously mentioned, $\beta_{TA_t * D_t}$ is the basis of our hypothesis (H_1). It measures the difference in the effect of a poultry disease on the bilateral poultry trade when TA membership changes from 0 to 1. Intuitively, $\beta_{TA_t * D_t}$ captures the extent to which TAs mitigate (or exacerbate) the effect of a disease on trade. Thus, when $\beta_{TA_t * D_t} > 0$, it indicates that TA members experience less severe negative trade effects than non-TA counterparts during a disease event. It is important to clarify that, since we are using semilogarithmic models with binary variables, for large changes, we conduct the following calculation to obtain the elasticities:

$$(3.8) \qquad \left(e^{\beta_i}-1\right)*100$$

H_2: $\beta_{TA_t*D_{t-n}} > 0$. *TAs help with quicker recovery of trade from disease events.*

Assuming that TAs play a role only during a disease event is not very realistic. Trade disruptions resulting from disease events often linger beyond the outbreak period. Because of the rapport and coordinated health and safety protocols among partners, TAs could help expedite the restoration of normal trade relations among members. As we have alluded to earlier on, there exists anecdotal evidence attesting to this phenomenon. H_2 is tested for both diseases using a series of lagged *(t-n)* $D_{i,t}$ variables to measure the role of TAs on delayed disease effects on bilateral poultry trade. We inferred our choice of lag structure from the disease events data. A simple analysis of the data reveals that HPAI outbreaks have an average duration of 6.9 months (median of four months) and ND has an average of 4.9 months (median of three months). Given these medians, we considered using short-term lags of three to six months for both diseases, adequately capturing the early impacts on trade. This range effectively encompasses ND's average duration. Meanwhile, HPAI's mean duration of 6.9 months suggests we should also consider longer-term lags of six to nine months, addressing both the typical and extended duration outbreaks. This approach ensures we capture the full spectrum of each disease's impact on trade. Ultimately, we settled for three, six-, and nine-month lags for both diseases. We included these diseases lags and their interactions with TA in the theoretically consistent equation (3.4). Intuitively, we are testing how TAs modify the effects of past disease events on current trade. The significance of $\beta_{TA_t*D_{t-n}}$ tests H_2. A positive value suggests that TA countries recover quicker from the trade impacts of disease events, while a negative value would indicate prolonged negative effects within TAs.

Data

For the empirical analysis, we integrate data from multiple sources. Bilateral poultry trade data are obtained from the Trade Data Monitor (TDM). To prepare the data for a gravity analysis, commodities accounting for less than 1% of annual bilateral trade were excluded to reduce the prevalence of zero trade observations, which can complicate analysis and obscure important economic insights. Additionally, non-recognized trading partners were also eliminated. These were eliminated because, beyond bilateral trade data, data on their other variables necessary for our analysis is nonexistent (e.g., the International Organization for Standardization country codes). These are important panel identifiers for gravity analysis. Our refined dataset is an unbalanced panel comprising monthly trade data on 212 countries and territories, covering 12 poultry product commodities, as detailed in Table B1, from 2013 to 2022. Detailed within the TDM dataset are trade values, quantities, commodity types, and year and month of transaction, categorized at the HS six-digit level for chicken and turkey, and at the four-digit level for eggs and egg products.

Disease event data for HPAI and ND are sourced from the World Organization for Animal Health, offering detailed monthly records starting in 2005. This dataset includes information on affected countries, number of flocks impacted, outbreak frequency, and the outbreak's nature (zoonotic or otherwise), specifically focusing on non-endemic cases. This information facilitated the construction of exporter-specific monthly indicators for both HPAI and ND. These indicators are used to capture the trade marginal effects of these disease events. According to our descriptive analysis presented in Table B2, HPAI and ND incidents impact approximately 14% and 3% of bilateral trade flows, respectively. Figure 3.1 illustrates the timing of HPAI and ND occurrences among the top ten poultry-exporting countries, which account for 78% of total poultry exports. Notably, for each of these top exporters, there are no instances where both disease events occur simultaneously.

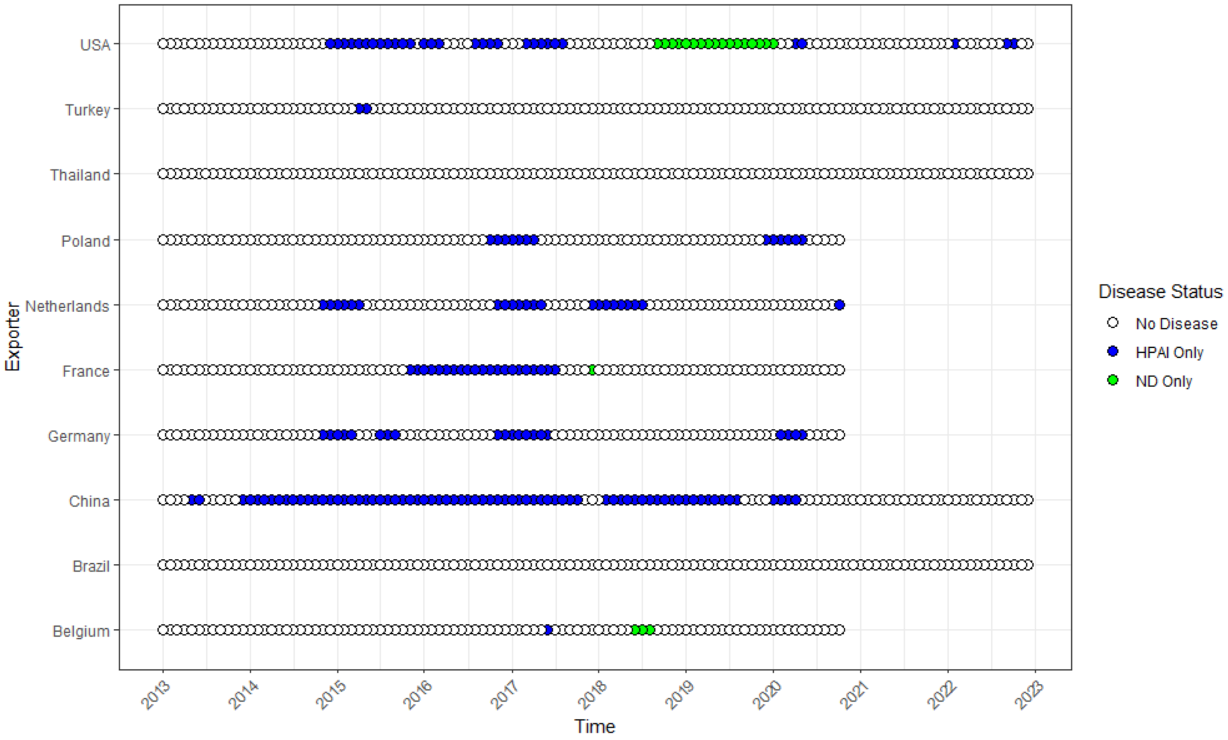

Figure 3.1. Timing of HPAI and ND events for the top 10 exporting countries

Trade agreement data are sourced from Mario Larch's Regional Trade Agreements Database, a comprehensive repository of both multilateral and bilateral trade agreements reported to the WTO from 1950 to 2022. This database includes 570 trade agreements, categorized into seven distinct types, such as customs unions and free trade areas. It also details membership changes, including accessions and withdrawals. With data on bilateral trade relationships across 280 countries, the database provides over five million observations. A TA binary variable is used to denote the presence of a trade agreement between trading partners, estimating its marginal impact on poultry trade. Table B2 reveals that approximately 68% of bilateral poultry trade occurs between countries engaged in some form of TA.

To address exporter-importer (trading pair) heterogeneity, we utilized geographic data from the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII) database. This dataset provides a range of variables critical for controlling trade costs, including population-weighted distance between countries (*distw*), dummy variables for shared borders (*contig*), common official language (*comlangoff*), significant minority language overlap (*comlangethno)*, post-1945 common colonizer (*comcol*), post-1945 colonial ties (*col45*), any colonial links (*colony*), current colonial relationships (*curcol*), and historical or current country unification (*smctry)*. To incorporate economic size effects, GDP data for exporters and importers were sourced from the World Bank Development Indicators Database, alongside country regions, enabling the creation of region-specific dummy variables to mitigate regional heterogeneity.

In line with Thompson et al. (2020), our analysis incorporates poultry trade variables that extend beyond trading pair-specific factors. *Share*, representing a country's annual proportion of global poultry exports, serves as a proxy for an exporter's market significance, which is critical in influencing trade restriction decisions by trading partners. Additionally, *OutYear*, quantifying concurrent disease events within a given year, acts as a global indicator of poultry health. After integrating these diverse data sources, our final dataset covers the period from 2013 to 2022.

Empirical Results

The empirical results are organized in the three subsections. In the first subsection the first hypothesis (H_1) was tested using aggregated poultry data. Given the panel data structure, REM and FEM are estimated. Subsequently, a Hausman misspecification test is conducted to test for endogeneity, revealing a preference for the FEM due to identified individual effects. Given the limitation of the FEM covered in the methodology section, the HT was estimated to take advantage of both within and between variation. To capture product-specific heterogeneity, we tested H_1 at the individual poultry product level by running separate models for each of the 12 products in the second subsection. Since the explanatory variables are consistent across all analyses and there is no strong theoretical basis to expect significant correlation in the error terms between products, this approach was deemed appropriate. In the last subsection, we conclude the result section by testing H_2 - that TAs help with trade recovery in the face of poultry disease events. To test H_2, we rely on the theoretically consistent HT model and aggregated poultry data.

Testing H_1 - Aggregated Poultry Products

Table 3.2 reports the results of the effect of TAs on bilateral trade for aggregated poultry products during HPAI and ND events. To ensure robustness in the findings, the results are presented for three model specifications. All models control additional variables as detailed in Appendix B (Table B2). Comparing columns (2) - (4), we can notice that both the size and statistical significance of the estimated parameters are comparable across the three specifications.

The TA coefficients have a positive effect on the value of bilateral poultry trade across all three econometric models. The coefficients for TA are consistently positive and highly significant, with values of 0.190 in both the FEM and HT models, and a slightly lower coefficient of 0.103 in the REM model. This finding underscores the trade-enhancing effects of TAs, suggesting that countries within such agreements experience 11% more trade (exp(0.19) – 1)*100), likely due to reduced trade barriers and increased market access facilitated by these agreements.

The impact of HPAI on poultry trade for countries that are not in a TA is negative and significant across all models, with coefficients close to -0.035. This indicates that HPAI outbreaks in exporting countries are associated with a reduction in bilateral poultry trade, reflecting the disease's detrimental impact on poultry exports. This can be a result of a combination of exporter supply shortages and importer responses (Thompson et al., 2020). Perhaps surprisingly, ND's effect on trade is positive and significant in all models, indicating that ND outbreaks in exporting countries are associated with an increase in bilateral poultry trade. This counterintuitive result might reflect complex dynamics in the global poultry market, possibly including increases in advantageous trading as a result of more affordable products that some importing partners are willing to accept (Thompson et al., 2020).

Table 3.2. Effect of TAs under HPAI and ND events for Aggregated Poultry Products

Covariates	(1) FEM	(2) REM	(3) HT
TA	0.190***	0.103***	0.190***
	(0.022)	(0.200)	(0.021)
HPAI	-0.036***	-0.034***	-0.035***
	(0.010)	(0.010)	(0.010)
TA*HPAI	-0.053***	-0.050***	-0.053***
	(0.012)	(0.012)	(0.012)
ND	0.039**	0.035*	0.040**
	(0.020)	(0.019)	(0.019)
TA*ND	0.077***	0.083***	0.077***
	(0.026)	(0.026)	(0.026)
Observations	603,724	603,724	603,724

The dependent variable is the log of bilateral poultry trade ($lnX_{ij,t}$*). All regressions include the same set of control variables which are included in the Appendix section in Table A3. FEM - Fixed Effects, REM - Random Effects, and HT - Hausman Taylor. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Hausman Misspecification tests - (* $\chi^2(7) = 251, p = 0.000$*).*

Turning to our parameters of interest, we see that the interaction term between TA and HPAI is consistently negative and significant. This result is intriguing as it suggests that while

TAs generally promote trade, their presence does not mitigate the negative impact of HPAI on poultry trade; in fact, it appears to exacerbate it. This could imply that the mechanisms through which TAs enhance trade are not effective in countering the trade disruptions caused by health crises such as HPAI, or that TA member countries impose stricter trade restrictions in response to such outbreaks. This finding is in contrast to our *apriori* expectations. By smoothening the implementation of SPS measures between trading pairs, one would expect TAs to somehow mitigate HPAI effects on trade. Important to note here is that this result shows the average response between trading pairs and does not necessarily imply that bilateral poultry trade falls for all trading pairs during HPAI disease events. The interaction term between TA and ND shows a positive and significant effect across all the three models. This indicates that TAs mitigate the adverse trade effects of ND or potentially leverage the disease's market effects to enhance trade further.

In summary, these findings provide nuanced insights into the role of TAs in modifying the trade impacts of poultry diseases. While TAs enhance overall trade levels, their interaction with disease outbreaks reveals complex dynamics: exacerbating the negative impacts of HPAI while mitigating or leveraging the effects of ND to promote trade. This could be due to differences in the diseases themselves including perceived risk (e.g., zoonotic potential) or the effectiveness of TA provisions in handling these diseases.

Testing H_1 - Disaggregated Poultry Products

To capture product-specific heterogeneity in the effect of TAs on trade, we further conducted our analysis at the individual poultry product level. For convenience, Table 3.3 displays only the results for the theoretically consistent HT model. All other results for different model specifications are in Appendix B (see Table B3 and Table B4). The results across the 12 poultry product categories reveal a complex interplay between TAs, HPAI, ND, and their interaction effects on trade. TAs exhibit a predominantly positive influence on the trade of various poultry products, such as Shell Eggs, Egg Products, both Fresh and Frozen Whole Chicken, and Cooked Chicken. This positive effect is consistent with the theoretical expectation that TAs, by facilitating lower trade barriers and improved market access, would enhance trade flows. However, the impacts of HPAI and ND on these products are heterogeneous. Consistent with our aggregate analysis, HPAI's effect is largely negative, significantly reducing trade in Shell Eggs, Egg Products, Cooked Turkey, and Cooked Chicken, while unexpectedly increasing trade in Frozen Chicken Parts. Conversely, ND generally has a positive impact, significantly increasing trade in Egg Products, Frozen Chicken Parts, and Frozen Turkey Parts, indicating differing market dynamics or perceptions of risk associated with ND.

Now, turning our attention to understanding the effect of TAs during poultry disease events. For both diseases, the significance[2] of the interaction term (β_{TA*D}) tests $H_{1.}$ Crucially, the results reveal that while TAs do not generally mitigate the diseases' negative effects across most products, they exhibit positive effects in certain product poultry categories. TAs significantly mitigate the effect of both diseases on the trade of two of the most traded products, namely, Frozen Chicken Parts and Cooked Chicken, constituting 19.14% and 13.97% of poultry product exchanges, respectively. This might be an indication of TA enhanced change in product mix, as more importers demand more of these two products at the expense of other products. Maybe cooked and frozen chicken products are perceived as safer by importers. Also, probably due to

---

[2] Once interaction effects are added, the more critical thing is the significance of the interaction terms, not the terms that were used to compute the interactions. For example. If β_{TA*D} is insignificant and we have added the interaction, this simply means that, when TA = 0, the effect of the disease is insignificant, but it may be significant when TA =1.

the inherent higher demand for these two products, there might be well established TA protocols to smoothen their exchange even during an animal health crisis.

Table 3.3. Effects of TAs and diseases on disaggregated poultry products trade

	Hausman Taylor					
	RTA	HPAI	RTA*HPAI	ND	RTA*ND	Obs.
Shell Eggs	0.304***	-0.100***	-0.018	-0.117**	-0.039	73,793
	(0.063)	(0.026)	(0.033)	(0.050)	(0.071)	
Eggs Products	0.414***	-0.168***	0.045	0.171**	0.010	45,059
	(0.095)	(0.036)	(0.043)	(0.075)	(0.095)	
Whole Chicken: Fresh	-0.156	0.086	-0.077	0.108	0.028	25,172
	(0.132)	(0.075)	(0.079)	(0.149)	(0.168)	
Whole Chicken: Frozen	0.218***	-0.021	-0.127***	-0.056	-0.017	60,459
	(0.072)	(0.033)	(0.040)	(0.068)	(0.087)	
Chicken Parts: Fresh	0.053	0.070	-0.223***	-0.144	0.150	36,887
	(0.096)	(0.055)	(0.060)	(0.121)	(0.141)	
Chicken Parts: Frozen	0.204***	0.040**	0.144***	0.093***	(0.039)**	115,017
	(0.037)	(0.017)	(0.024)	(0.033)	(0.011)	
Whole Turkey: Frozen	-0.110	0.007	-0.253***	-0.125	0.247	12,663
	(0.182)	(0.067)	(0.083)	(0.100)	(0.156)	
Whole Turkey: Fresh	0.039	-0.029	-0.059	0.200	-0.080	21,624
	(0.201)	(0.082)	(0.087)	(0.130)	(0.162)	
Turkey Parts: Frozen	-0.006	-0.025	-0.066*	0.158***	0.273***	45,940
	(0.069)	(0.032)	(0.040)	((0.055)	(0.083)	
Cooked Turkey	0.145*	-0.089*	-0.022	-0.063	0.081	42,735
	(0.086)	(0.046)	(0.052)	(0.080)	(0.098)	
Cooked Chicken	0.351***	-0.082***	0.100***	0.082	0.101***	83,755
	(0.059)	(0.028)	(0.033)	(0.061)	(0.033)	
Cooked Other	0.031	-0.028	-0.008	0.028	0.072	40,620
	(0.097)	(0.047)	(0.053)	(0.166)	(0.181)	

*The dependent variable is the log of bilateral poultry trade $lnX_{ij,t}$. All regressions include the same set of control variables which are included in the Appendix section in Table A3. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.*

Testing H_2 - Aggregated Poultry Products

In the previous two subsections, we presented results on the role TAs play during poultry disease events. While these results shed light on the role of TAs in mitigating concurrent disease effects, they did not reflect the importance of TAs on the lingering effects of these disease events. The second hypothesis (H_2) tests the effect of TAs on trade recovery by including lagged disease indicators in the theoretically consistent HT model, using aggregate poultry data (Table 3.4).

Table 3.4. Effect of RTAs on disease impacts on bilateral poultry trade

	Hausman Taylor Model					
	(1)		(2)		(3)	
	One Disease Lag		Two Disease Lags		Three Disease Lags	
Covariates	HPAI	ND	HPAI	ND	HPAI	ND
TA_t	0.110***	0.110***	0.085**	0.085**	0.065**	0.065**
	(0.025)	(0.025)	(0.028)	(0.028)	(0.030)	(0.030)
D_t	-0.047***	0.027	-0.052***	0.041	-0.044***	0.044
	(0.012)	(0.028)	(0.013)	(0.030)	(0.013)	(0.030)
TA_t*D_t	-0.040***	0.050	-0.027*	0.019	-0.037**	0.002
	(0.014)	(0.034)	(0.015)	(0.035)	(0.015)	(0.036)
D_{t-3}	-0.009	0.040	-0.020	0.072**	-0.026*	0.062*
	(0.012)	(0.278)	(0.014)	(0.035)	(0.014)	(0.036)
TA_t*D_{t-3}	0.003	0.053	0.011	-0.008	0.003	-0.012
	(0.014)	(0.034)	(0.016)	(0.041)	(0.016)	(0.041)
D_{t-6}	-	-	-0.003	-0.068	-0.010	-0.044
			(0.013)	(0.030)	(0.015)	(0.036)
TA_t*D_{t-6}	-	-	0.040***	0.135***	0.047***	0.073*
			(0.015)	(0.035)	(0.017)	(0.042)
D_{t-3}	-	-	-	-	-0.005	-0.024
					(0.014)	(0.030)
TA_t*D_{t-9}	-	-	-	-	0.032**	0.106***
					(0.010)	(0.034)
Observations	447,168	447,168	379,643	379,643	337,225	337,225

*The dependent variable is the log of value of bilateral poultry trade $lnX_{ij,t}$. All regressions include the same set of control variables which are included in the Appendix section in Table A3. HT- means Hausman Taylor. Total disease effect is estimated by summing concurrent and lagged D_t coefficients. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.*

Noteworthy, the results substantiate the arguments we made in our hypothesis (H_2) that disease events exert lingering effects on trade, suggesting that the influence of RTAs extends beyond the immediate context of an outbreak. Focusing on columns 6 and 7 (the model with all three lags), the analysis reveals a positive effect of TAs on mitigating the negative impacts of HPAI on trade, six to nine months post-outbreaks, as evidenced by the coefficients of 0.047 and 0.032 for the second and third lags, respectively. This indicates that, while the immediate aftermath of HPAI may pose challenges to trade, the presence of TAs contributes significantly to trade recovery in the medium to long-term. The mechanisms behind this could involve TA-facilitated cooperative measures such as improved SPS, which enhance confidence and trade flow restoration.

Conversely, the interaction between TAs and ND showcases a complex pattern. The initial lag interaction term is negative (-0.012), although not statistically significant, suggesting a limited mitigating effect of TAs on the trade impacts of ND. However, as time progresses, the positive and significant coefficients for the second (0.073) and third (0.106) lags highlight a substantial TA role in counteracting the adverse trade effects of ND over time. This suggests a delayed, but increasingly positive contribution of TAs to stabilizing and enhancing poultry trade following ND outbreaks.

Incorporating up to nine months lags to assess prolonged impact of diseases on trade reveals a crucial trend: a notable reduction in dataset observations. This decline is particularly significant given ND's limited incidence in our dataset, affecting merely 3% of bilateral transactions. The necessity to include multiple lags for a thorough temporal analysis inadvertently leads to fewer usable observations, a challenge exacerbated by ND's sparse initial data. This loss of data, especially pronounced as we delve into longer-term effects, likely underpins the mixed findings for ND's trade impacts across varied lags. Results for ND should therefore be interpreted with caution.

Our findings for H_2 underscore the critical role of TAs in not only fostering trade under normal circumstances, but also in mitigating the lingering effects of poultry diseases on trade. The delayed yet positive effects observed, particularly in the context of HPAI, highlight the importance of considering the temporal dimension in assessing the efficacy of TAs in mitigating contagious disease effects on trade.

Sensitivity Analysis

One major concern when analyzing trade data is the effect of outliers on policy parameters. Recall that, as mentioned in the data section, poultry products accounting for less than 1% of annual bilateral trade were excluded from the sample. Another potential source of outliers comes from countries with minimal export contributions. Given the nature of our analysis, excluding these countries entirely could lead to a loss of much-needed variation in our TA variable. Nevertheless, to assess the sensitivity of our results to export outliers, we performed a sensitivity analysis for the first hypothesis (H_1) using aggregated poultry data. We applied the Hausman-Taylor (HT) estimator to the top ten exporters. Table 3.5 presents a side-by-side comparison of the HT results for the full sample and those limited to the top ten exporters. The results indicate that our findings are relatively stable and comparable. The coefficients for TA, HPAI, and the interaction term TA*HPAI are consistent in both sign and significance. However, while the coefficients for ND and TA*ND remain positive, they are not statistically significant when focusing on the top ten exporters.

Table 3.5. Sensitivity of TAs and disease parameters to export outliers

	Hauman Taylor	
Covariates	Full Sample	Top 10 Exporters
TA	0.190***	0.230***
	(0.021)	(0.030)
HPAI	-0.035***	-0.048***
	(0.010)	(0.012)
TA*HPAI	-0.053***	-0.032**
	(0.012)	(0.014)
ND	0.040**	0.016
	(0.019)	(0.020)
TA*ND	0.077***	0.023
	(0.026)	(0.033)
Observations	603,724	290,314

*The dependent variable is the log of bilateral poultry trade ($\ln X_{ij,t}$). All regressions include the same set of control variables which are included in the Appendix section. HT - Hausman Taylor. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.*

Conclusion

We investigated whether TA members face less severe negative trade effects compared to their non-TA counterparts during poultry disease events using both aggregated poultry data, to observe general trends, and disaggregated data for specific product heterogeneities. Aggregate analysis showed TA members have less bilateral trade during HPAI events than non-TA counterparts, a somewhat counterintuitive finding. This may be because previous outbreaks have shown HPAI outbreaks to be more drastic, making HPAI one of, if not the most important poultry disease. Also, HPAI outbreaks are on average two months longer than ND and also affect almost five times more bilateral transactions. Importer restrictions are therefore likely to be stricter even for those countries bound by TAs. In contrast, during ND events, TA members have more bilateral trade than non-TA members. Disaggregated product analysis revealed a generally negative role of TAs during HPAI, consistent with aggregate findings. We also find mitigated trade effects for key products like frozen chicken parts and cooked chicken during both HPAI and ND events.

Animal diseases usually present lingering effects. The second hypothesis tested whether TAs help expedite trade recovery. Using aggregate data and the HT model with lagged disease indicators, we found that TA members tend to recover faster from lagged disease effects, especially during HPAI events.

The results of this study, while revealing, should be put into perspective. Notably, during animal disease outbreaks, some trade agreements explicitly allow for regionalization[3], which helps mitigate the impact of disease on trade. However, the potential effect of regionalization as a buffer against disease-related trade disruptions was not considered in our analysis. Additionally, the phase-in effects of RTAs, which could influence the timing and extent of trade facilitation and disease impact mitigation, were also not accounted for. Furthermore, the study did not differentiate between types of trade agreements, which may have varying degrees of trade-enhancing capabilities.

Despite these limitations, the results highlight TAs' key role in reducing the impacts of poultry diseases like HPAI and ND on poultry trade, particularly in aiding recovery. Managing the impacts of poultry disease outbreaks requires robust coordination and harmonization of SPS standards within TAs. Developing specific protocols for disease outbreaks, ensuring timely updates, and conducting joint training sessions for SPS officials are vital steps. Furthermore, disease-specific trade protocols within TAs should include tailored measures for both HPAI and

---

[3] Regionalization refers to the practice of identifying and designating specific geographic areas or regions as disease-free or disease-affected within a country. Instead of imposing blanket trade bans on all animal products from an entire country where a disease outbreak occurs, regionalization allows for targeted restrictions based on the actual risk areas.

ND. The broad adoption of responsive strategies like regionalization can alleviate the severity of trade restrictions under HPAI, making them more targeted and less disruptive, particularly within TAs. These actions are essential to sustaining trade flows and minimizing economic disruptions during poultry disease outbreaks. Future research should incorporate the different TA types and their phase-in effects to gain a deeper insight into the effectiveness of TAs during animal health emergencies.

Chapter 4 - Conclusions

Contagious animal diseases can substantially impact livestock supply chains and erode consumer and producer welfare. As the demand for animal sourced foods surge, due to increasing global population and growth in incomes, animal diseases management will continue to be of importance. Within the realm of animal diseases impacts, the current work consists of two main themes: (1) Estimating the potential welfare impacts of African swine fever (ASF), and (2) Understanding the role of Trade Agreements (TAs) during highly pathogenic poultry diseases. Jointly, these two studies attempt to gain insights on the value of animal health investments.

The first essay shows that the economic impact of ASF on the U.S. swine supply chain could be devastating. Our analysis shows net welfare loss ranging between \$277 million to \$4,077 million per year depending on the scenario. These economic impacts depend on the size of the outbreak, consumers reactions, and response of trading partners. Our scenario analysis shows that consumers can benefit from reduced prices when a production shock is small and export restrictions are minimal, while producers lose. For a large outbreak, model estimates show consistent welfare losses for both consumer and producers with the magnitude depending on the severity of export restrictions. By knowing the economic impacts of ASF, policy makers can better prepare for control and response efforts. The findings also show the importance of maintaining access to foreign markets during an animal health crisis.

To maintain access to foreign markets during disease events, exporting countries can rely on existing relationships with trading partners. For example, even though the ongoing 2022 HPAI outbreak in the United States is the worst in history based on number of birds culled, trade restrictions were not as bad as experienced in 2014/2015 due to negotiations with trading partners. Bilateral frameworks like TAs can be important under such circumstances. The second essay analyzes the role of TAs in mitigating trade effects of highly pathogenic poultry diseases. Results show that the role that TAs play depends on the nature of the disease as well as the product category. Model estimates show no mitigating role of TA on contemporaneous effect of HPAI but do for ND in general. Product specific analysis shows TA mitigating HPAI effects for the most traded poultry products. Also, TAs help with trade recovery for both diseases.

While managing the impact of animal diseases is an ongoing challenge, understanding these impacts is crucial for shaping effective response strategies. Our results reveal the varied consequences of ASF throughout the swine supply chain, providing insight for crafting targeted strategies in prevention, control, and mitigation. Given the substantial costs associated with large-scale animal health investments, this research highlights the need for preemptive planning and prioritization. Furthermore, the findings underscore the importance of nurturing bilateral trade relationships, which can play a vital role in mitigating trade impacts associated with animal diseases.

References

Introduction References

Casal, J., Tago, D., Pineda, P., Tabakovski, B., Santos, I., Benigno, C., Huynh, T., Ciaravino, G., & Beltran-Alcrudo, D. (2022). Evaluation of the economic impact of classical and African swine fever epidemics using OutCosT, a new spreadsheet-based tool. *Transboundary and Emerging Diseases*, *69*(5), e2474–e2484.

Charostad, J., Rukerd, M. R. Z., Mahmoudvand, S., Bashash, D., Hashemi, S. M. A., Nakhaie, M., & Zandi, K. (2023). A comprehensive review of highly pathogenic avian influenza (HPAI) H5N1: An imminent threat at doorstep. *Travel Medicine and Infectious Disease*, 102638.

Cole, L., & Stepien, M. (2021a). *USDA Statement on Confirmation of African Swine Fever in Haiti*.

Cole, L., & Stepien, M. (2021b). *USDA Statement on Confirmation of African Swine Fever in the Dominican Republic*.

Dee, S., Brands, L., Nerem, J., Schelkopf, A., Spronk, G., Kikuti, M., Corzo, C., & Havas, K. (2023). Improvements in swine herd biosecurity reduce the incidence risk of porcine reproductive and respiratory syndrome virus in breeding herds in the Midwestern United States. *Journal of the American Veterinary Medical Association*, *1*(aop), 1–6.

European Centre for Disease Prevention and Control (ECDC). (2022, September 30). *Avian influenza overview June – September 2022*. https://www.ecdc.europa.eu/en/publications-data/avian-influenza-overview-june-september-2022

Johnson, K. K., Hagerman, A. D., Thompson, J. M., & Kopral, C. A. (2015). Factors influencing export value recovery after highly pathogenic poultry disease outbreaks. *International Food and Agribusiness Management Review*, *18*, 27–42.

Lee, J., Schulz, L. L., Hoffman, E., & Tonsor, G. T. (2022). How can reporting on foreign animal diseases affect meat purchases? The case of African swine fever. *Agricultural and Resource Economics Review*, 1–23.

NPPC. (2023). National Pork Producers Council. https://nppc.org/the-pork-industry/

Padilla, S., & MacLachlan, M. (2023, February 24). *Highly Pathogenic Avian Influenza (HPAI) and trade considerations*. USDA Economic Research Service. Presentation at the Agricultural Outlook Forum, Arlington, VA.

Schulz, L. L., & Tonsor, G. T. (2015). Assessment of the economic impacts of porcine epidemic diarrhea virus in the United States. *Journal of Animal Science*, *93*(11), 5111–5118.

USDA. (2024). https://ask.usda.gov/s/article/What-is-the-most-consumed-meat-in-the-world

U.S. Department of Agriculture, Animal and Plant Health Inspection Service. (2024, June 20). *Confirmations of highly pathogenic avian influenza in commercial and backyard flocks*. https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-disease-information/avian/avian-influenza/hpai-2022/2022-2024-hpai-commercial-backyard-flocks

Valdes-Donoso, P., & Jarvis, L. S. (2022). Combining epidemiology and economics to assess control of a viral endemic animal disease: Porcine Reproductive and Respiratory Syndrome (PRRS). *PloS One*, *17*(9), e0274382.

WOAH. (2024). WOAH - World Organization for Animal Health. https://www.woah.org/en/article/animal-health-through-an-economic-lens/

Essay 1 References

AgMRC - Pork Processing. (2021). https://www.agmrc.org/commodities-products/livestock/pork/pork-processing

Balagtas, J. V., & Kim, S. (2007). Measuring the Effects of Generic Dairy Advertising in a Multi-Market Equilibrium. *American Journal of Agricultural Economics, 89*(4), 932–946.

Beach, R. H., Zhen, C., Piggott, N. E., Wohlgenant, M. K., Viator, C. L., & Cates, S. C. (2007). An Economic Analysis of the Effectiveness of the Pork Checkoff Program. *Final Report, National Pork Board, Des Moines, IA.*

Bekkerman, A., Brester, G. W., & Tonsor, G. T. (2019). An alternative approach to measuring demand changes in meat markets. *International Food and Agribusiness Management Review*, *22*(3), 397–412.

Berentsen, P., Dijkhuizen, A., & Oskam, A. (1992). A dynamic model for cost-benefit analyses of foot-and-mouth disease control strategies. *Preventive Veterinary Medicine, 12*(3–4), 229–243.

Brester, G. W., Marsh, J. M., & Atwood, J. A. (2004). Distributional impacts of country-of-origin labeling in the US meat industry. *Journal of Agricultural and Resource Economics,* 206-227.

Brown, V. R., Miller, R. S., McKee, S. C., Ernst, K. H., Didero, N. M., Maison, R. M., Grady, M. J., & Shwiff, S. A. (2021). Risks of introduction and economic consequences associated with African swine fever, classical swine fever and foot-and-mouth disease: A review of the literature. *Transboundary and Emerging Diseases*, *68*(4), 1910–1965.

Carriquiry, M., Elobeid, A., & Hayes, D. (2023). *National impacts of a domestic outbreak of foot and mouth disease and African swine fever in the United States*.

Casal, J., Tago, D., Pineda, P., Tabakovski, B., Santos, I., Benigno, C., Huynh, T., Ciaravino, G., & Beltran-Alcrudo, D. (2022). Evaluation of the economic impact of classical and African swine fever epidemics using OutCosT, a new spreadsheet-based tool. *Transboundary and Emerging Diseases*, *69*(5), e2474–e2484.

Chenais, E., Boqvist, S., Emanuelson, U., von Brömssen, C., Ouma, E., Aliro, T., Masembe, C., Ståhl, K., & Sternberg-Lewerin, S. (2017). Quantitative assessment of social and economic impact of African swine fever outbreaks in northern Uganda. *Preventive Veterinary Medicine*, *144*, 134–148.

Christen, C. (2021, January 29). *Top Pork Producing States: Who Is the Largest Pork Producer in the U.S.?* https://sentientmedia.org/top-pork-producing-states/

Cole, L., & Stepien, M. (2021a). *USDA Statement on Confirmation of African Swine Fever in Haiti*.

Cole, L., & Stepien, M. (2021b). *USDA Statement on Confirmation of African Swine Fever in the Dominican Republic*.

Dixon, L. K., Stahl, K., Jori, F., Vial, L., & Pfeiffer, D. U. (2020). African swine fever epidemiology and control. *Annual Review of Animal Biosciences*, *8*, 221–246.

Gardner, B. L. (1975). The farm-retail price spread in a competitive food industry. *American Journal of Agricultural Economics*, *57*(3), 399-409.

Hess, W. R. (2019). African swine fever. *The Arboviruses*, 19–38.

Kashyap, S., Schulz, L. L., Johanns, A. F., & Crespi, J. M. (2024). *The economic impacts of African Swine Fever in the U.S. pork industry: A CARD model analysis.* Center for Agricultural and Rural Development, Iowa State University.

Lee, J., Schulz, L. L., Hoffman, E., & Tonsor, G. T. (2022). How can reporting on foreign animal diseases affect meat purchases? The case of African swine fever. *Agricultural and Resource Economics Review*, 1–23.

Lemieux, C. M., & Wohlgenant, M. K. (1989). Ex ante evaluation of the economic impact of agricultural biotechnology: The case of porcine somatotropin. *American Journal of Agricultural Economics*, *71*(4), 903-914.

Lusk, J. L., & Anderson, J. D. (2004). Effects of country-of-origin labeling on meat producers and consumers. *Journal of Agricultural and Resource Economics*, 185–205.

Lusk, J. L., & Norwood, F. B. (2012). Speciesism, altruism and the economics of animal welfare. *European Review of Agricultural Economics*, *39*(2), 189-212.

Lusk, J. L., & Tonsor, G. T. (2021). Supply and demand indices and their welfare implications. *Q Open*, *1*(1), qoaa008.

Mason-D’Croz, D., Bogard, J. R., Herrero, M., Robinson, S., Sulser, T. B., Wiebe, K., Willenbockel, D., & Godfray, H. C. J. (2020). Modelling the global economic consequences of a major African swine fever outbreak in China. *Nature Food*, *1*(4), 221–228.

Meuwissen, M. P., Horst, S. H., Huirne, R. B., & Dijkhuizen, A. A. (1999). A model to estimate the financial consequences of classical swine fever outbreaks: Principles and outcomes. *Preventive Veterinary Medicine*, *42*(3–4), 249–270.

Mulumba-Mfumu, L. K., Saegerman, C., Dixon, L. K., Madimba, K. C., Kazadi, E., Mukalakata, N. T., Oura, C. A., Chenais, E., Masembe, C., & Ståhl, K. (2019). African swine fever: Update on Eastern, Central and Southern Africa. *Transboundary and Emerging Diseases*, *66*(4), 1462–1480.

Muth, R. F. (1964). The derived demand curve fora productive factor and the industry supply curve. *Oxford Economic Papers*, *16*(2), 221-234.

Nguyen-Thi, T., Pham-Thi-Ngoc, L., Nguyen-Ngoc, Q., Dang-Xuan, S., Lee, H. S., Nguyen-Viet, H., Padungtod, P., Nguyen-Thu, T., Nguyen-Thi, T., & Tran-Cong, T. (2021). An assessment of the economic impacts of the 2019 African swine fever outbreaks in Vietnam. *Frontiers in Veterinary Science*, *8*, 686038.

Paarlberg, P. L., Seitzinger, A. H., Lee, J. G., & Mathews Jr, K. H. (2009). *Supply reductions, export restrictions, and expectations for hog returns in a potential classical swine fever outbreak in the United States*.

Pendell, D. L., Brester, G. W., Schroeder, T. C., Dhuyvetter, K. C., & Tonsor, G. T. (2010). Animal identification and tracing in the United States. *American Journal of Agricultural Economics*, *92*(4), 927–940.

Piggott, N. E. (2003). Measures of precision for estimated welfare effects for producers from generic advertising. *Agribusiness: An International Journal*, *19*(3), 379–391.

Saatkamp, H., Berentsen, P., & Horst, H. (2000). Economic aspects of the control of classical swine fever outbreaks in the European Union. *Veterinary Microbiology*, *73*(2–3), 221–237.

Sánchez-Vizcaíno, J., Mur, L., & Martínez-López, B. (2012). African swine fever: An epidemiological update. *Transboundary and Emerging Diseases*, *59*, 27–35.

Schroeder, T. C., & Tonsor, G. T. (2011). Economic impacts of Zilmax® adoption in cattle feeding. *Journal of Agricultural and Resource Economics*, 521–535.

Suh, D. H., & Moss, C. B. (2017). Decompositions of corn price effects: Implications for feed grain demand and livestock supply. *Agricultural Economics*, *48*(4), 491–500.

Tao, D., Sun, D., Liu, Y., Wei, S., Yang, Z., An, T., Shan, F., Chen, Z., & Liu, J. (2020). One year of African swine fever outbreak in China. *Acta Tropica*, *211*, 105602.

Tonsor, G. T., & Schroeder, T. C. (2015). Market impacts of E. coli vaccination in US feedlot cattle. *Agricultural and Food Economics*, *3*, 1-15.

USDA ERS - Sector at a Glance. (2023). https://www.ers.usda.gov/topics/animal-products/hogs-pork/sector-at-a-glance/

Vanthemsche, P. (1994). *Experiences with swine fever control in Belgium*. *2223*, 6979.

Wang, Y., Massa, O. I., & Stewart, S. L. (2024). Time-varying reaction of US meat demand to animal disease outbreaks. *Applied Economic Perspectives and Policy*.

Wohlgenant, M. K. (1993). Distribution of gains from research and promotion in multi-stage production systems: The case of the US beef and pork industries. *American Journal of Agricultural Economics*, *75*(3), 642–651.

Wohlgenant, M. (2005). Market Modeling of the Effects of Adoption of New Swine Waste Management Technologies in North Carolina. *Unpublished, North Carolina State University*.

Wohlgenant, M. K. (2011). Consumer demand and welfare in equilibrium displacement models. *The Oxford Handbook of the Economics of Food Consumption and Policy*, 0–44.

Yang, Q., Martínez-López, B., & Scoglio, C. (2023). *P08. 3 A novel approach to estimate the animal movement networks: Illustration for the swine industry in Iowa (US) and implications for disease prevention and control using a network-based model*. GeoVet 2023 International Conference.

You, S., Liu, T., Zhang, M., Zhao, X., Dong, Y., Wu, B., Wang, Y., Li, J., Wei, X., & Shi, B. (2021). African swine fever outbreaks in China led to gross domestic product and economic losses. *Nature Food*, *2*(10), 802–808.

Essay 2 References

Agnosteva, D. E., Anderson, J. E., & Yotov, Y. V. (2014). *Intra-national trade costs: Measurement and aggregation*. National Bureau of Economic Research.

Baier, S. L., & Bergstrand, J. H. (2007). Do free trade agreements actually increase members' international trade? *Journal of International Economics*, *71*(1), 72–95.

Baldwin, R., & Taglioni, D. (2006). *Gravity for dummies and dummies for gravity equations*.

Bastola, U. (2015). *Essays on international agricultural development*. Washington State University.

Beverelli, C., Keck, A., Larch, M., & Yotov, Y. V. (2018). *Institutions, trade and development: A quantitative analysis*.

Blayney, D. P., Dyck, J. H., & Harvey, D. J. (2006). *Economic effects of animal diseases linked to trade dependency*. United States Department of Agriculture.

Çakır, M., Boland, M. A., & Wang, Y. (2018). The economic impacts of 2015 Avian influenza outbreak on the US Turkey industry and the loss mitigating role of free trade agreements. *Applied Economic Perspectives and Policy*, *40*(2), 297–315.

Cartín-Rojas, A. (2012). Transboundary animal diseases and international trade. *International Trade from Economic and Policy Perspective*, *143*, 166.

Dobrowolska, A., & Brown, S. (2016). The economic impact of the 2015 avian influenza outbreak on US egg prices. *Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management. St. Louis, MO.* http://www.farmdoc.illinois.edu/nccc134

Dohlman, E., Hansen, J., & Boussios, D. (2022). *USDA agricultural projections to 2031*.

Egger, P. H., & Nigai, S. (2015). Structural gravity with dummies only: Constrained ANOVA-type estimation of gravity models. *Journal of International Economics*, *97*(1), 86–99.

Farris, J., Morgan, S., & Beckman, J. (2024). *Evaluating the Effects of Nontariff Measures on Poultry Trade*.

Gharleghi, B., & Shafighi, N. (2020). Do regional trade agreements increase trade? Empirical evidence from the Asia–Pacific region. *Economic Affairs*, *40*(3), 419–435.

Grant, J. H., & Lambert, D. M. (2008). Do regional trade agreements increase members' agricultural trade? *American Journal of Agricultural Economics*, *90*(3), 765–782.

Junker, F., Ilicic-Komorowska, J., & Van Tongeren, F. (2009). Impact of animal disease outbreaks and alternative control practices on agricultural markets and trade: The case of FMD. *OECD Food, Agriculture and Fisheries Papers No. 19, OECD Publishing, Paris,*.

Knowles, N. J., Samuel, A. R., Davies, P. R., Midgley, R. J., & Valarcher, J.-F. (2005). Pandemic strain of foot-and-mouth disease virus serotype O. *Emerging Infectious Diseases*, *11*(12), 1887.

Krueger, A. O. (1997). Free trade agreements versus customs unions. *Journal of Development Economics*, *54*(1), 169–187.

Larch, M., & Yotov, Y. V. (2023). *Estimating the Effects of Trade Agreements: Lessons from 60 Years of Methods and Data*.

Marsh, T. L., Wahl, T., & Suyambulingam, T. (2005). Animal disease outbreaks and trade bans. *World Trade Organization Impacts on US Farm Policy*.

Miller, M., Gerval, A., Hansen, J., & Grossen, G. (2022). Poultry Expected To Continue Leading Global Meal Imports as Demand Rises. *Amber Waves: The Economics of Food, Farming, Natural Resources, and Rural America*, *2022*.

Morgan, N., & Prakash, A. (2006). International livestock markets and the impact of animal disease. *Rev Sci Tech*, *25*(2), 517–528.

Ramos, S., MacLachlan, M., & Melton, A. (2017). Impacts of the 2014-2015 highly pathogenic avian influenza outbreak on the US poultry sector. *Livestock Dairy Poultry Outlook*.

Saatkamp, H., Berentsen, P., & Horst, H. (2000). Economic aspects of the control of classical swine fever outbreaks in the European Union. *Veterinary Microbiology*, *73*(2–3), 221–237.

Thompson, J. M. (2018). Effects of regionalized trade restrictions on quantity exported during a highly pathogenic avian influenza event. *Journal of Agricultural and Applied Economics*, *50*(2), 270–289.

Thompson, J. M., Pendell, D. L., Hagerman, A. D., & Johnson, K. K. (2020). International Trade Implications of Highly Pathogenic Poultry Disease Events. *Agricultural and Resource Economics Review*, *49*(3), 517–537.

Tinbergen, J. (1962). *Shaping the world economy; suggestions for an international economic policy*.

Webb, M., Gibson, J., & Strutt, A. (2018). The impact of diseases on international beef trade: Market switching and persistent effects. *Food Policy*, *75*, 93–108.

Yotov, Y. V., Piermartini, R., & Larch, M. (2016). *An advanced guide to trade policy analysis: The structural gravity model*. WTO iLibrary.

Chapter 5 - Appendix for the potential economic welfare impact of ASF on the U.S. swine supply chain

This appendix documents the supplementary material referenced in the first essay. It consists of two sections. The first section contains base values, elasticities, and shares used in the EDM. Section 2 presents equations used for the estimation of some of the quantity transmission elasticities.

Appendix A Section 1: EDM base values and parameters

Table A1. Price and Quantity Definitions and Estimates

Symbol	Definition	Estimate
Q^r	Quantity of retail pork, million pounds (retail weight)	4,374.21
Q^{wh}	Quantity of wholesale pork, million pounds (carcass weight)	6,904.50
Q_i^{wh}	Quantity of wholesale pork imports, million pounds (carcass weight)	358.37
Q_e^{wh}	Quantity of wholesale pork exports, million pounds (carcass weight)	1,540.64
Q^s	Quantity of pork obtained from slaughter hogs, million pounds (live weight)	8,333.20
Q_i^s	Quantity of slaughter hog imports, million pounds (live weight)	62.12
Q^{ch}	Quantity of pork obtained from cull hogs, million pounds (live weight)	242.65
Q^f	Quantity of pork obtained from feeder pigs, million pounds (live weight)	1,518.44
Q_i^f	Quantity of feeder pig imports, million pounds (live weight)	62.69
Q^w	Quantity of pork obtained from weaners, million pounds (live weight)	340.87
I_s	Sow inventory (1,000 heads)	2,918.80
P^r	Price of retail pork, $/lb	4.79
P^{wh}	Price of wholesale pork, $/lb	2.03
P^s	Price of slaughter hog, $/lb (live weight)	0.64
P_i^s	Price of slaughter hog imports, $/lb (live weight)	0.76
P^{ch}	Price of cull hogs, $/lb (liveweight)	0.63
P^f	Price of feeder pigs, $/lb (live weight)	2.76
P_i^f	Price of feeder pig imports, $/lb (live weight)	0.68
P^w	Price of weaners, $/lb (live weight)	6.01

All quantity and price values reflect 2022 Q1 averages obtained from the Livestock Marketing Information Center. All prices of live animals were converted to $/lb.

Table A2. Supply and Demand Elasticity Definitions and Estimates

Elasticity	Description	Value	Source
η^r	Own-price elasticity of demand for retail pork	-0.66	(Bekkerman et al., 2019)
ϵ^r	Own-price elasticity of supply for retail pork	0.15	(Lusk & Tonsor, 2021)
η^{wh}	Own-price elasticity of demand for wholesale pork	-0.71	(Schroeder & Tonsor, 2011)
ϵ^{wh}	Own-price elasticity of supply for wholesale pork	0.44	(Schroeder & Tonsor, 2011)
η_i^{wh}	Own -price elasticity of demand for wholesale pork imports	-0.71	(Schroeder & Tonsor, 2011))
ϵ_i^{wh}	Own-price elasticity of supply for wholesale pork imports	1.41	(Hahn et al., 2019)
η_e^{wh}	Own-price elasticity of demand for wholesale pork exports	-0.89	Pendell et al 2010
η^s	Own price elasticity of demand for slaughter hogs	-0.51	(Schroeder & Tonsor, 2011)
ϵ^s	Own price elasticity of supply for slaughter hogs	0.41	(Schroeder & Tonsor, 2011)
η_i^s	Own price elasticity of demand for slaughter hog imports	-0.80	Aurthor Estimate
ϵ_i^s	Own-price elasticity of supply for market hog imports	0.201	Beach et al., 2007
η^{ch}	Own price elasticity of demand for cull hogs	-0.51	Same as slaughter hogs
ϵ^{ch}	Own price elasticity of supply for cull hogs	0.41	Same as slaughter hogs
η^f	Own price elasticity of demand for feeder pigs	-0.70	Aurthor Estimate
ϵ^f	Own price elasticity of supply for feeder pigs	0.40	(Hahn et al., 2019)
η_i^f	Own price elasticity of demand for feeder pig imports	-0.60	Aurthor Estimate
ϵ_i^f	Own-price elasticity of supply for feeder pig imports	0.20	(Wohlgenant, 2005)
η^w	Own-price elasticity of demand for weaners	-0.50	Aurthor Estimate
ϵ^{gpw}	Elasticity of weight per weaner w.r.t price of weaner	0.008	Beach et al., 2007
ϵ^{sipw}	Elasticity of sow inventory w.r.t to price of weaners	0.09	Beach et al., 2007

Table A3. Quantity Transmission Elasticity Definitions and Estimates

Elasticity	Definition	Estimate	Source
τ^{whr}	Percentage change in retail pork supply given a 1% change in wholesale pork supply	0.96	Pendell et al., 2010
τ^{rwh}	Percentage change in wholesale pork demand given a 1% change in retail pork demand	0.98	Pendell et al., 2010
τ^{swh}	Percentage change in wholesale pork supply given a 1% change in slaughter hog supply	0.96	Pendell et al., 2010
τ^{chwh}	Percentage change in wholesale pork supply given a 1% change in cull hog supply	0.90	Author's calculation
τ^{whs}	Percentage change in slaughter hog demand given a 1% change in wholesale pork demand	0.96	Pendell et al., 2010
τ^{fs}	Percentage change in market hog supply given a 1% change in feeder pig supply	1.00	Author's calculation
τ^{sis}	Percentage change in imported slaughter hog demand given a 1% change in slaughter hog demand	0.80	Aurthor's Estimate
τ^{whch}	Percentage change in cull hog demand given a 1% change wholesale pork demand	1.05	Aurthor's Estimate
τ^{sich}	Percentage change in cull hog supply given a 1% change in sow inventory	1.01	Author's calculation
τ^{sf}	Percentage change in feeder pig demand given a 1% change slaughter hog demand	0.96	Aurthor's Estimate
τ^{wf}	Percentage change in feeder pig supply given a 1% change in weaner supply	1.07	Author's Calculation
τ^{fif}	Percentage change in imported feeder pig demand given a 1% change in feeder pig demand	0.94	Aurthor's Estimate
τ^{fw}	Percentage change in weaner demand given a 1% change in feeder pig demand	0.97	Aurthor's Estimate
τ^{iff}	Percentage change in feeder pig supply given a 1% change in feeder pig imports	0.93	Aurthor’s Calculation

Table A4. Swine and Pork Production, Import and Export Shares

Definition	Estimate	Source
U.S. producers' share of total feeder pig quantity	0.96	Author's Calculation
U.S. producers' share of total slaughter hog quantity	0.99	Author's Calculation
U.S processors' share of total pork quantity	1.175153	Author's Calculation
Exports' share of total pork quantity	0.276008	Author's Calculation
Imports' share of total pork quantity	0.058508	Author's Calculation
Cull hog share of total pork quantity	0.042347	Author's Calculation

Table A5. Percentage changes in endogenous variables for the large ASF outbreak 60 % export loss scenario[a]

	Prices				Quantities			
Endogenous Variable	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Retail pork	2.06	2.06	-0.12	-0.85	-2.36	-2.36	-0.92	-0.44
Wholesale pork	0.65	0.65	0.05	-0.16	-2.78	-2.78	-0.94	-0.32
Imported wholesale pork	-2.62	-2.62	-1.77	-1.48	-3.70	-3.70	-2.49	-2.09
Exported wholesale pork	_*a*	_*a*	_*a*	_*a*	-60.58	-60.58	-60.04	-59.86
Slaughter hogs	0.21	0.21	-0.40	-0.60	-9.20	-9.20	-7.12	-6.42
Imported slaughter hogs	-13.77	-13.77	-12.10	-11.55	-2.77	-2.77	-2.43	-2.32
Cull hogs	-7.79	-7.79	-5.93	-5.31	-5.37	-5.37	-4.38	-4.05
Feeder pigs	-9.82	-9.82	-9.41	-9.27	-8.39	-8.40	-6.68	-6.11
Imported feeder pigs	-17.93	-17.93	-15.92	-15.24	-3.55	-3.55	-3.15	-3.02
Weaners	-22.57	-22.57	-20.99	-20.46	-3.28	-3.28	-2.41	-2.12
Sows	-	-	-	-	-2.12	-2.12	-1.92	-1.85

Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] *We assume a 60% export loss and 1% loss in retail demand*

Table A6: Percentage changes in endogenous variables for the large ASF outbreak 90% export loss scenario[a]

Endogenous Variable	**Prices**				**Quantities**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Retail pork	1.93	1.93	-0.25	-0.98	-2.27	-2.27	-0.83	-0.35
Wholesale pork	0.61	0.61	0.01	-0.19	-2.67	-2.67	-0.83	-0.21
Imported wholesale pork	-3.24	-3.24	-2.38	-2.09	-4.56	-4.56	-3.36	-2.95
Exported wholesale pork	_*a*	_*a*	_*a*	_*a*	-90.55	-90.55	-90.01	-89.83
Slaughter hogs	-0.04	-0.04	-0.65	-0.85	-12.17	-12.17	-10.09	-9.40
Imported slaughter hogs	-19.35	-19.35	-17.69	-17.13	-3.89	-3.89	-3.56	-3.44
Cull hogs	-10.16	-10.16	-8.30	-7.68	-7.25	-7.25	-6.26	-5.93
Feeder pigs	-14.37	-14.37	-13.96	-13.82	-11.28	-11.28	-9.57	-8.99
Imported feeder pigs	-25.36	-25.36	-23.34	-22.66	-5.02	-5.02	-4.62	-4.49
Weaners	-32.63	-32.63	-31.04	-30.51	-4.27	-4.27	-3.40	-3.11
Sows	-	-	-	-	-3.03	-3.03	-2.82	-2.76

Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] *We assume a 90% export loss and 1% loss in retail demand.*

Table B3: Percentage changes in endogenous variables for the large ASF outbreak staggered export losses scenario[a]

Endogenous Variable	**Prices**				**Quantities**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Retail pork	1.93	2.00	-0.12	-0.79	-2.27	-2.32	-0.92	-0.48
Wholesale pork	0.61	0.63	0.05	-0.14	-2.67	-2.73	-0.94	-0.38
Imported wholesale pork	-3.24	-2.93	-1.77	-1.17	-4.56	-4.13	-2.49	-1.65
Exported wholesale pork	_*a*	_*a*	_*a*	_*a*	-90.55	-75.56	-60.04	-44.88
Slaughter hogs	-0.04	0.08	-0.40	-0.47	-12.17	-10.69	-7.12	-4.93
Imported slaughter hogs	-19.35	-16.56	-12.10	-8.75	-3.89	-3.33	-2.43	-1.76
Cull hogs	-10.16	-8.98	-5.93	-4.12	-7.25	-6.31	-4.38	-3.11
Feeder pigs	-14.37	-12.10	-9.41	-7.00	-11.28	-9.84	-6.68	-4.66
Imported feeder pigs	-25.36	-21.65	-15.92	-11.53	-5.02	-4.29	-3.15	-2.28
Weaners	-32.63	-27.60	-20.99	-15.43	-4.27	-3.78	-2.41	-1.63
Sows	-	-	-	-	-3.03	-2.58	-1.92	-1.40

Note: Percentage changes are based upon 2022 prices and quantities for swine and pork. Export prices are assumed to be equal to domestic prices.

[a] *We assume a 90% export loss in Q1, 75% in Q2, 60% in Q3, and 45% in Q4 and 1% loss in retail demand across all 4 quarters.*

Appendix A Section 2: Quantity Transmission Elasticity Estimation Equations

Here, we present equations used for the estimation of some of the quantity transmission elasticities. These elasticities were estimated using Ordinary Least Squares with logged quantities assuming constant elasticities.

Percentage change in wholesale pork supply given a 1% change in cull hog supply:

(A1) $$EQ^{wh} = \beta_1 + \tau^{chwh} EQ^{ch}$$

Percentage change in market hog supply given a 1% change in feeder pig supply:

(A2) $$EQ^{s} = \beta_1 + \tau^{fs} EQ^{f}$$

Percentage change in cull hog supply given a 1% change in sow inventory

(A3) $$EQ^{ch} = \beta_1 + \tau^{sich} EI^{s}$$

Percentage change in feeder pig supply given a 1% change in weaner supply

(A4) $$EQ^{f} = \beta_1 + \tau^{wf} EQ^{w}$$

Percentage change in feeder pig supply given a 1% change in feeder pig imports

(A5) $$EQ^{f} = \beta_1 + \tau^{iff} EQ_i^{f}$$

.

Chapter 6 - Appendix for the importance of Trade Agreements during Poultry Disease Events

This appendix documents the supplementary material referenced in the second essay, including the poultry products used in the analyses, gravity model variables, and additional regression results.

Table B1. Poultry Product Categories used in the Gravity Analyses

Product Short Name	Product Name	HS Code
Whole Chicken: Fresh	Meat and Edible Offal of Chickens, Not Cut in Pieces, Fresh or Chilled	20711
Whole Chicken: Frozen	Meat and Edible Offal of Chickens, Not Cut in Pieces, Frozen	20712
Chicken Parts: Fresh	Chicken Cuts and Edible Offal (Including Livers) Fresh or Chilled	20713
Chicken Parts: Frozen	Chicken Cuts and Edible Offal (Including Livers) Frozen	20714
Whole Turkey: Frozen	Turkeys, Not Cut in Pieces, Frozen	20725
Whole Turkey: Fresh	Turkey Cuts and Edible Offal (Including Livers), Fresh or Chilled	20726
Turkey Parts: Frozen	Turkey Cuts and Edible Offal (Including Liver) Frozen	20727
Shell Eggs	Birds’ Eggs, In Shell, Preserved or Cooked	407
Eggs Products	Birds’ Eggs, Not in Shell, and Egg Yolks, Fresh, Dried, Cooked by Steam etc., Molded, Frozen or Otherwise Preserved, Sweetened or Not	408
Cooked Turkey	Meat or Meat Offal of Turkeys, Prepared or Preserved N.E.S.O.I.	160231
Cooked Chicken	Prepared or Preserved Chicken Meat, Meat Offal or Blood, N.E.S.O.I.	160232
Cooked Other	Meat or Meat Offal of Chickens, Ducks, Geese and Guineas, Prepared or Preserved, N.E.S.O.I.	160239

Table B2. Descriptive Statistics for Variables Used in the Gravity Analyses

Name	Variable Description	Unit	HT[b]-Grouping	Mean	Min	Max
Bilateral Poultry Trade[a]	Value of poultry products exported	USD	TV[c], Exogenous	16,145	0	150,000,000
Regional Trade Agreement (RTA)	Binary variable indicating if country trading pairs had a trade agreement	0,1	TV, Exogenous	0.676	0	1
Highly Pathogenic Avian Influenza (HPAI)	Binary variable indicating if HPAI was reported	0,1	TV, Endogenous	0.141	0	1
Newcastle Disease (ND)	Binary variable indicating if ND was reported	0,1	TV, Endogenous	0.027	0	1
GDP exporter[e]	GDP of exporter	USD	TV, Exogenous	2,650	843	25,400,000
GDP importer[e]	GDP of importer	USD	TV, Exogenous	842,000	36,800	25,400,000
Share	Annual share of global export market	%	TV, Endogenous	0.048	0.000	0.329
OutYear$_t$	Number of simultaneous disease events in year t	Count	TV, Exogenous	27.25	15	45
Distw	Weighted geographical distance between pairs	km	TIV[d], Exogenous	3,615.474	114.637	19,781.390
Contiguity	Binary variable for contiguity	0,1	TIV, Exogenous	0.201	0	1
Comlang_off	Binary for common official language	0,1	TIV, Exogenous	0.203	0	1
Comlang_ethno	Binary for share ethnical language	0,1	TIV, Exogenous	0.219	0	1
Colony	Binary for colonial link	0,1	TIV, Exogenous	0.086	0	1
Comcol	Binary for common colonizer after 1945	0,1	TIV, Exogenous	0.041	0	1
Col1945	Binary for colonial relationship after 1945	0,1	TIV, Exogenous	0.047	0	1
Curcol	Binary for current colonial relationship	0,1	TIV, Exogenous	0.007	0	1
Landlocked	Binary for land lockedness	0,1	TIV, Exogenous	0.084	0	1
Smctry	Binary for pair were/are the same country	0,1	TIV, Exogenous	0.067	0	1
Africa	Binary for if exporter is in Africa	0,1	TIV, Exogenous	0.027	0	1
America	Binary for if exporter is in America	0,1	TIV, Exogenous	0.178	0	1
Asia	Binary for if exporter is in Asia	0,1	TIV, Exogenous	0.109	0	1
Europe	Binary for if exporter is in Europe	0,1	TIV, Exogenous	0.667	0	1
Pacific	Binary for if exporter is in Pacific	0,1	TIV, Exogenous	0.020	0	1

Source: Author Calculations

[a] *Dependent Variable*

[b] *HT Grouping - Hausman Taylor variable classification*

[c] *TV: Time Variant*

[d] *TIV: Time Invariant*

[e] *Values for GDP exporter and GDP importer are in million USD*

Table B3. Effect of TAs on disease impacts on bilateral trade of disaggregated poultry products trade (Fixed Effects Model)

	Fixed Effects					
	TA	**HPAI**	**TA*HPAI**	**ND**	**ND*HPAI**	**Obs.**
Shell Eggs	0.307***	-0.101***	-0.018	-0.117**	-0.040	73 793
	(0.064)	(0.027)	(0.034)	(0.051)	(0.072)	
Eggs Products	0.424***	-0.169***	0.045	0.170**	0.011	45 059
	(0.097)	(0.036)	(0.043)	(0.076)	(0.096)	
Whole Chicken: Fresh	-0.154	0.086	-0.078	0.108	0.029	25 172
	(0.134)	(0.076)	(0.081)	(0.152)	(0.171)	
Whole Chicken: Frozen	0.216***	-0.020	-0.128***	-0.056	-0.018	60 459
	(0.073)	(0.033)	(0.041)	(0.070)	(0.090)	
Chicken Parts: Fresh	0.058	0.069	-0.229***	-0.146	0.152	36 887
	(0.098)	(0.056)	(0.061)	(0.123)	(0.143)	
Chicken Parts: Frozen	0.203***	0.039**	0.144***	0.092***	0.040*	115 017
	(0.037)	(0.018)	(0.024)	(0.033)	(0.021)	
Whole Turkey: Frozen	-0.067	0.007	-0.256***	-0.125	0.239	12 663
	(0.190)	(0.069)	(0.086)	(0.103)	(0.161)	
Whole Turkey: Fresh	0.057	-0.030	-0.058	0.198	-0.078	21 624
	(0.205)	(0.084)	(0.088)	(0.132)	(0.165)	
Turkey Parts: Frozen	-0.004	-0.025	-0.066	0.157***	0.273***	45 940
	(0.070)	(0.032)	(0.041)	(0.056)	(0.084)	
Cooked Turkey	0.147*	-0.090*	-0.022	-0.065	0.082	42 735
	(0.087)	(0.047)	(0.526)	(0.081)	(0.100)	
Cooked Chicken	0.358***	-0.083***	0.101***	0.080	0.248***	83 755
	(0.060)	(0.028)	(0.034)	(0.062)	(0.076)	
Cooked Other	0.028	-0.029	-0.008	0.029	0.716	40 620
	(0.101)	(0.048)	(0.054)	(0.170)	(0.184)	

The dependent variable is the log of bilateral poultry trade $lnX_{ij,t}$*. All regressions include the same set of control variables which are included in Table B2. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.*

Table B5: Effect of TAs under HPAI and ND events for Aggregated Poultry Products – Complete Results

Covariates	**(1) FEM**	**(2) REM**	**(3) HT**
TA	0.190***	0.103***	0.190***
	(0.022)	(0.200)	(0.021)
HPAI	-0.036***	-0.034***	-0.035***
	(0.010)	(0.010)	(0.010)
TA*HPAI	-0.053***	-0.050***	-0.053***
	(0.012)	(0.012)	(0.012)
ND	0.039**	0.035*	0.040**
	(0.020)	(0.019)	(0.019)
TA*ND	0.077***	0.083***	0.077***
	(0.026)	(0.026)	(0.026)
Out Year	-0.004***	-0.004***	-0.004***
	(0.000)	(0.000)	(0.000)
Share	0.020***	0.017***	0.020***
	(0.001)	(0.000)	(0.001)
Contiguity	-	1.241***	1.732***
		(0.070)	(0.244)
Comlang_off	-	0.051	-0.032
		(0.085)	(0.294)
Comlang_ethno	-	0.424**	0.478*
		(0.082)	(0.285)
Colony	-	-0.526***	-0.450
		(0.108)	(0.361)
Comcol	-	-0.112	-0.208
		(0.087)	(0.305)
Col945		0.241*	0.068
		(0.141)	(0.474)
Curcol	-	-0.036	0.185
		(0.347)	(1.114)
Smctry	-	-0.307**	-0.390
		(0.108)	(0.354)
landlocked	-	-0.528***	-0.759***
		(0.069)	(0.238)

Distance	-	-0.185*** (0.023)	-0.235** (0.101)
America	-	2.435*** (0.087)	3.510*** (0.320)
Asia	-	1.292*** (0.087)	2.635*** (0.340)
Europe	-	1.892*** (0.079)	2.765*** (0.337)
Pacific	-	2.028*** (0.137)	2.701*** (0.494)
GDP exporter	0.73*** (0.26)	0.286*** (0.023)	0.928*** (0.250)
GDP importer	0.94*** (0.065)	-0.185*** (0.023)	0.884*** (0.062)
Observations	603,724	603,724	603,724

*The dependent variable is the log of bilateral poultry trade ($lnX_{ij,t}$). All regressions include the same set of control variables which are included in Table B3. FEM - Fixed Effects, REM - Random Effects, and HT - Hausman Taylor. Standard errors reported in parentheses. *,**,*** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Hausman Misspecification tests - ($X^2(7) = 251, p=0.000$).*