Food Policy 126 (2024) 102655

Contents lists available at ScienceDirect

Food Policy

journal homepage: www.elsevier.com/locate/foodpol

Biological lags and market dynamics in vertically coordinated food supply chains: HPAI impacts on U.S. egg prices

James L. Mitchell [a,*], Jada M. Thompson [a], Trey Malone [b]

[a] Department of Agricultural Economics and Agribusiness, University of Arkansas Division of Agriculture, United States
[b] Department of Agricultural Economics, Purdue University, United States

ARTICLE INFO

JEL Codes:
Q11
Q13
Q18

Keywords:
Supply chain dynamics
Retail egg prices
Biological lags
Avian Influenza

ABSTRACT

It is well known that livestock production involves long biological lags. Failure to account for these biological lags can result in the misspecification of supply chain relationships and adjustments to market shocks, which can have significant implications for policy decisions. An example is the 2022 Highly Pathogenic Avian Influenza (HPAI) event that caused high mortality rates in domestic poultry supply chains and reduced egg production. We use the 2022–2023 HPAI event to highlight the implications of misspecification of disease dynamics in agri-food systems. Specifically, we examine the impact of HPAI on U.S. egg prices in 2022–2023. To do this, we estimate a hedonic model of retail egg prices that controls for quality, regional, and temporal factors. The model allows for the effect of HPAI on egg prices to accumulate over time, reflecting the biological adjustment to replace commercial flocks that were depopulated because of HPAI. The preferred model specifications estimate that HPAI caused weekly retail egg prices to increase on average by 5.3 percent. We calculate changes in consumer surplus to provide economic context for the main econometric results. When we extend these results to consumer surplus, we find that models that ignore the cumulative nature of HPAI estimate gains in consumer surplus, and models that ignore the post-outbreak recovery of layer inventories overestimate the consumer surplus loss by a factor of 3 to 4. Our findings have important policy implications, particularly concerning disease outbreaks that can significantly impact agricultural production. This analysis emphasizes the importance of understanding context-specific outcomes for agri-food supply chain research.

1. Introduction

Determining the impacts of market shocks on agri-food systems requires a comprehensive understanding of agri-food supply chains and their many interconnected factors. Failure to accurately represent these complex relationships can result in misspecification that significantly affects the precision of price and production predictions when estimating the size and scope of vertical disruptions (Wahdat and Lusk, 2023). By extension, the recent food supply chain literature has heavily explored the relationship between market structure and food system resiliency (Hadachek et al., 2024; Karakoc et al., 2023; Stevens and Teal, 2023). Biological constraints on livestock and poultry production from disease outbreaks are an important dimension that has garnered less emphasis in the literature on supply chain resiliency yet holds significant implications for understanding supply chain dynamics.[1] This is especially true given the ongoing global concerns about African swine fever and foot and mouth disease. Indeed, prior studies indicate that infectious diseases such as the 2013 U.S. outbreak of porcine epidemic diarrhea virus in the hog industry can significantly increase consumer prices, underscoring the importance of biosecurity for swine producers (Schulz and Tonsor, 2015; Pudenz et al., 2019).

The 2022 Highly Pathogenic Avian Influenza (HPAI) outbreak in U.S. poultry production poignantly illustrates the importance of unforeseen biological disruptions in supply chain resiliency, with the Consumer Price Index (CPI) for eggs increasing 66.5% less than a year after the first reported outbreak in February 2022 (Subramaniam et al., 2023). This

* Corresponding author at: 217 Agriculture Building, Fayetteville, AR 72701, United States.
E-mail address: jlmitche@uark.edu (J.L. Mitchell).

[1] There is a long history of literature investigating the consequences of biological constraints on agricultural output (e.g., Nerlove, 1979). This literature mostly focused on price expectations and supply chain adjustment mechanisms that often take form of a distributed lag model, akin to the prior studies on price transmission in agricultural markets (von Cramon-Taubadel and Goodwin, 2021). Epidemiology and the delayed effects of livestock diseases adds a wrinkle to these traditional models that has mostly been ignored.

https://doi.org/10.1016/j.foodpol.2024.102655
Received 8 September 2023; Received in revised form 30 May 2024; Accepted 2 June 2024
Available online 13 June 2024

article emphasizes that the supply chain literature would benefit from an understanding of the relationship between the biological production lags that involve managing disease outbreaks and price impacts. For our purposes, "biological production lags" refer to the time it takes for agricultural production systems to respond to changes in inputs, such as animal reproduction, plant growth, livestock weight gain, and egg production. Understanding the relationship between disease and retail prices is particularly important, as animal disease outbreaks can, directly and indirectly, lead to large consumer price changes, threatening food security and affordability (Acosta et al., 2020, 2023; Hennessy and Marsh, 2021; Seeger et al., 2021; Thompson et al., 2019a; Xiong et al., 2021). This article pays particular attention to the importance of changes in flock sizes and their delayed effect on egg production and prices.

Our study demonstrates that failure to account for biological production lags leads to models that underestimate the impacts of HPAI on egg prices. Specifically, we estimate several econometric models with data from the 2022 HPAI event and show how misspecification is magnified in welfare analysis. Considering six alternative specifications of the biological adjustment to HPAI, econometric models estimate a price response ranging from a 2.76% decline in egg prices to a 20.79% increase in egg prices. This misestimation is not merely an academic concern; it has important policy implications that can affect decisions surrounding disease control, market regulation, and emergency response in the agricultural sector. Indeed, policy response variation can be costly, underscoring the importance of accurately assessing price responses to disease outbreaks. As such, we then use model specifications based on different biological lags to calculate compensating variation, highlighting the scale of the differences associated with each misspecified model. Our findings reveal that misspecification of biological lags leads to losses in consumer surplus that are overestimate by a factor of 4.

This analysis aims to foster a nuanced approach to econometrically modeling disease outbreaks that recognizes the complex biological dynamics at play. We arrive at these insights by estimating a hedonic pricing model of retail egg prices that controls for quality, regional, and temporal factors. One of our main contributions is how we choose to measure the impacts of HPAI. We introduce six alternative specifications for HPAI, each contributing distinct insights into the effects of the outbreak. The first two specifications consider single-week effects, capturing the current week's impact on egg prices. We compare our findings across a binary variable denoting a confirmed outbreak and the total number cases (birds), where the latter accounts for flock size. We consider these the most naïve specifications. We then consider the cumulative effects of the previous week's HPAI outbreaks without specifying when they should stop affecting egg prices. Lastly, we introduce cumulative biological effects, accounting for the six-month adjustment period required to replace a flock depopulated because of HPAI, based on biological constraints in commercial egg production. Our multifaceted approach allows us to understand both the immediate and lagged effects of HPAI outbreaks on egg prices, acknowledging the complexity and nuances of the agri-food supply chain and the biological realities that govern it.

This gap in the literature underscores the need for more nuanced food supply chain models, particularly since the frequency and impact of infectious disease emergence and reemergence within the agri-food system may increase in the future (Jones et al., 2008; Wang and Crameri, 2014). Several factors contribute to this outlook. As temperatures and humidity levels change, diseases and disease carrying vectors that were once limited to tropical and sub-tropical areas might find suitable conditions and habitats in regions that were previously unaffected or disease free, spilling over to agricultural production systems (Altizer et al., 2013). Deforestation and changes in land use can also alter the natural habitat of wildlife, leading to increased interactions between wildlife, livestock, and humans (Keesing et al., 2010). Additional intensive farming practices can then increase the risk of disease transmission as once an infectious agent gets introduced, it can spread rapidly due to the proximity of animals (Jones et al., 2013). Expanding global trade means that food products, plants, and animals are often transported over vast distances, which can introduce foreign pathogens and pests to new regions (Paini et al., 2016; Thompson, 2018).

Having highlighted these dynamics in the agri-food system, the remainder of this paper is organized as follows. Section 2 describes how the industrial organization of the U.S. layer industry contributes to the price impacts of biological lags. Sections 3 and 4 describe the methodology and data used in our empirical analysis. Section 5 presents the results of our study, offering evidence for the significant role of biological production lags in price estimation. Section 6 extends econometric results to an analysis of consumer welfare, highlighting the policy implications of our work. Finally, Section 7 concludes with recommendations for future studies, emphasizing the need for a context-specific understanding of food production systems to ensure accurate estimation of the impacts of various inputs on production and prices.

2. Background

Biology is intertwined with any food supply chain, and poultry is no different. Intensification of the U.S. layer industry started in the 1950s with the disaggregation of meat and egg birds. This shift allowed genetic selection to focus on egg lay rates and marketability. Egg production is carried out in layer houses, specialized facilities that provide adequate ventilation, space, and access to food and water. The three main types of layer systems are conventional (caged), enriched cages (more space per bird in each cage), and cage-free. Eggs produced on laying farms are often called shell eggs instead of hatching eggs (fertilized eggs) that are part of the bird replenishment chain. Shell eggs are diverted into either table eggs or breaker eggs. According to USDA's Agricultural Marketing Service (USDA-AMS), table eggs account for roughly 69.0 percent of egg utilization between retail consumers and food service, while processed eggs account for 29.3 percent (United Egg Producers, 2024). Table eggs are inspected, washed, graded (e.g., A.A., A, or B), and cartoned. Table eggs are typically sold at retail outlets. Breaker eggs are broken and processed into liquid, dried, or frozen products. These products can be sold at retail but are often used as an ingredient in other goods such as food or manufacturing. This supply chain is characterized in Fig. 1. Little U.S. egg production is exported, 3–4% (USDA-OCE, 2023), but this quantity has been growing.

The typical egg produced in the United States is a white, conventional egg predominantly laid by White Leghorn hens. Rhode Island Reds typically produce brown eggs. Both breeds typically have the highest lay rate for their respective egg color. Brown egg breeds tend to have a lower lay rate than the White Leghorn, which increases the cost to produce a dozen eggs, explaining the premium for these eggs. The content of the egg is the same regardless of the shell color. Differences in feed can change the fat content or yolk color. Additional market factors include outdoor access in production (e.g., free range) and feed type (e.g., organic, vegan fed, enriched Omega 3 fatty acids).

Part of the egg supply chain is the egg layer replenishment supply which rears replacement birds for layer houses during normal business periods and emergency restocking during business disruptions such as HPAI. Egg layer replenishment is characterized by genetic breeding lines that produce hatching eggs set at hatcheries. The stages range from great-grandparent birds down to parent stocks (also called breeders), with an increasing number of birds at each stage. Hybrid vigor in this breeding pyramid allows for the genetic selection of optimal traits. Fertilized chicken hatching eggs take 21 days to hatch once set. Female birds are transported to either pullet farms or to a cage-free complex until sexual maturity at 19–20 weeks of age. Pullets are moved to layer houses and will lay eggs until 12 to 15 months of age. At this time, a producer can molt the birds, which will stop egg production for a limited time, usually around 65 weeks of age, but can extend overall egg production until the hens are 18–24 months (about two years) old (USDA-

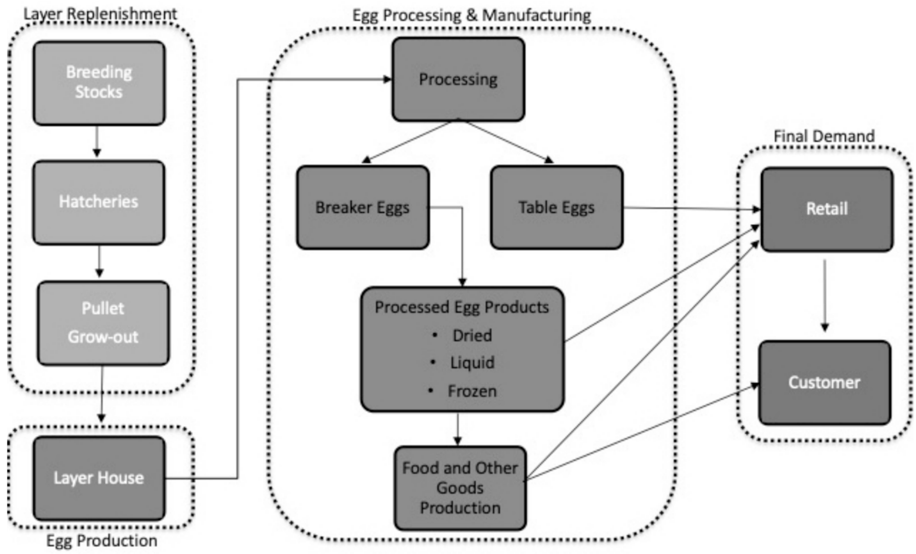

Fig. 1. U.S. Commercial Egg Industry Supply Chain.

NAHMS, 2014). At the end of the first or second production phase, these hens are sold as spent hens and harvested.

During a business disruption or disease event like HPAI, birds at all levels of the production supply chain can be impacted (Thompson et al., 2019b). Laying hens reduce production levels, replenishment pullets which can slow the restocking capacity, and breeder birds which influence hatching of new birds. Moreover, the biological lag to replace flocks depopulated by HPAI will depend on which segment is impacted the most by HPAI. For example, the time lag will be very different for an HPAI event that predominately impacts layers as opposed to an event that mostly impacts breeding flocks. Accounting for the supply chain impacts in understanding a disease event outside of the direct layer impacts, allows for a better understanding of the nuances of the supply chain.

In terms of market structure, a complete description of the industry is provided by USDA-APHIS (2011) and Watt Global Media (2022). Briefly, the US egg industry is largely integrated with many firms, but there are few larger firms including Cal-Maine Foods, Rose Acre Farms, and Hilandale Farms who combined account for 30 percent of hens produced in 2022 (Watt Global Media 2022). The majority, 64.4 percent, of farms are contracted where the company owns the birds and feed and the grower provides the building, utilities, and labor (USDA-APHIS, 2011). Larger farms are more likely to be company owned, predominantly for in-line breakers and on-site processing. Over time there has been an increase in consolidation in the egg industry for larger flock sizes, e.g., mean flock size was 300,000 in 1997 and 1,200,000 in 2017 (MacDonald, 2020). This can have an impact when a premises contracts a disease. Eggs are sold either through contracts or on the wholesale market. Egg prices that are contracted typically have some basis of the contract price deriving from the wholesale market, however these contracts are proprietary.

3. Methods

Before describing our empirical strategy, terminology from the epidemiology literature needs clarification. The term *disease event* distinguishes the time period between the first and last HPAI outbreak in 2022. Under international standards from the World Organization for Animal Health (WOAH), member countries and territories must report disease events of animal health significance (USDA-APHIS, 2022). HPAI in 2022 was a reportable disease event. We use *outbreak* to refer to a flock of birds infected with HPAI (USDA-APHIS, 2014). While a flock typically characterizes all the birds placed in a house at a given a time, for the purposes of this paper we will consider all birds on a premises (e.g., across multiple houses) to be one flock, as disease management treats all birds on one premises unilaterally regardless of what building they were housed. *Case* refers to a bird impacted by HPAI (USDA-APHIS, 2014). USDA does not test every bird in a flock for HPAI. Instead, USDA confirms infections at the flock level. The number of cases is the size of the flock impacted by HPAI. The variables we construct distinguish between the number of HPAI outbreaks and cases.

3.1. Empirical strategy

We approximate the relationship between national egg prices and HPAI with the following linear model:

$$\widetilde{Price}_{it} = \beta_o + \beta_1 HPAI_t + \gamma X_{it} + \delta Z_t + \varepsilon_{it}, \tag{1}$$

where $\widetilde{Price}_{it}$ is logged retail egg prices for egg type i, where type is defined by a combination of egg characteristics, and time period $t = 1, \ldots, T$, $HPAI_t$ denotes a measure of HPAI, X_{it} is a vector of egg characteristics, Z_t is a vector of time varying control variables, including seasonality and inflation, ε_{it} is the random error term, and β_1 is the quantity of interest.

With this approach, there are two main threats to identification. The first is that HPAI represents a downstream supply shock to the retail egg market. That is, HPAI outbreaks do not impact consumer demand for eggs. Evidence from previous HPAI events on purchasing behavior show little consumer demand impact (Beach et al., 2008). The two sources through which HPAI could impact consumer demand are food recalls and consumer awareness (Marsh et al., 2004; Lee et al., 2023). The 2022 and 2023 HPAI outbreaks affected farm-level production and were not linked to food recalls or contamination. As such, it is reasonable to assume HPAI did not impact consumer demand through food recalls. To the extent awareness translates to changes in demand, results from Kansas State University's Meat Demand Monitor provide a crude estimate of whether HPAI impacts consumer demand for eggs. Results about consumer awareness from February 2022 to December 2022 show that, among 16 protein issues, consumers consistently rank HPAI as one of the least important (Tonsor, 2022). Wang et al. (2024) find a delayed consumer demand response to HPAI for broiler meat but do not consider demand for eggs. They also do not state through what mechanism HPAI impacts consumer demand. If consumer awareness about HPAI did impact purchasing decisions, egg prices would decline. Failing to control for consumer awareness in the analysis would result in us underestimating the effects of HPAI as a supply shock. In the data section, we describe how we construct an index for consumer awareness as a control variable.

The second is that $HPAI_t$ measures the impacts of HPAI on egg prices independent of other sources of supply-side inflation. By definition, HPAI is a source of inflation to egg prices. At the same time, during the 2022 and 2023 HPAI outbreaks COVID-19 and the Ukraine War likely impacted egg prices. Without properly controlling for these other factors, any measure for $HPAI_t$ would capture the broader impacts of inflation on retail egg prices. Using the Consumer Price Index (CPI) as a time varying control variable for inflation (Z_t) would be a model misspecification because egg prices are included in the CPI calculation. The CPI less food and energy would throw out the factors separate from HPAI that could be impacting retail prices. We use the Prices Paid Index for Commodities and Services, Interest, Taxes, and Farm Wage Rates (PPITW) from USDA-NASS to capture other supply-side factors that could inflate egg prices. Further information on PPITW is provide in the next section of the paper.

3.2. HPAI specification

One of our contributions is how we choose to specify $HPAI_t$ based on USDA-APHIS (2023) event reporting. The first two variables we construct allow for the current week's HPAI outbreaks to impact the current week's egg prices. The first variable, which we denote $Flocks_t$, is a binary variable that equals 1 if there was a confirmed outbreak of HPAI in a commercial layer flock in week t and 0 otherwise. The second variable we construct equals the total number of HPAI cases (birds) during week t. We denote this specification $Birds_t$. The difference between the two variables is $Birds_t$ distinguishes between HPAI outbreaks based on the size of commercial layer flocks while $Flocks_t$ does not control for differences in flock sizes. $Birds_t$ and $Flocks_t$ do not control for past outbreaks.

Many researchers might choose these specifications, which treat each HPAI outbreak as a discrete, one-time market shock because it would be useful from the perspective of an event study analysis (Malone and Lusk, 2016; Malone et al., 2021). More specifically, a specification that treats HPAI as a discrete, one-time shock would appeal to a difference-in-difference estimator. However, such an approach is will not work for several reasons:

1. The effects of HPAI are lagged and cumulative. The egg supply chain does not carry excess layer capacity; it takes six months for a new flock to reach maturity and lay eggs, and each successive flock that is depopulated adds to the impact on egg prices (USDA-ERS, 2023b.
2. Defining the event for an event study is unclear. Is the event duration the time between the first and last outbreak? Is each outbreak a separate event?
3. An event study would need to distinguish events by the impact size or population affected by HPAI. If an event study were appropriate, it would need to weight each event by flock size.

The following HPAI variable specifications overcome these challenges.

The approach taken by USDA-APHIS for controlling and eradicating HPAI is stamping out (USDA-APHIS, 2022). WOAH defines stamping out as the depopulation of herds and flocks of animals that have confirmed or suspected infection of or exposure to disease (USDA-APHIS, 2022). When there is a confirmed case of HPAI, that flock is depopulated. Egg production from the depopulated flock is permanently lost until it can be replaced. This implies that previous HPAI outbreaks will continue to affect egg prices until the impacted flock is replaced. Each successive flock depopulated will have an additive effect on egg prices.

The next two specifications allow for previous week's HPAI outbreaks and cases to impact the current week's egg prices. We refer to these specifications as cumulative effects (impacts). The first variable, which we denote, $CFlocks_{it}$, represents the cumulative effect of the number of previously infected flocks, summing backward from the present week t to the first reported outbreak of HPAI. The second cumulative variable is denoted $CBirds_{it}$. Instead of counting the number of flocks, it sums up the total number of individual birds affected by HPAI from the first outbreak to the present week t. The cumulative impacts captured by $CFlocks_{it}$ and $CBirds_{it}$ allow for an adjustment in the supply chain from HPAI. A problem with these variables is there is no rule for when previous HPAI outbreaks should stop affecting egg prices.

The egg supply chain does not carry excess capacity of layers. When a layer flock is depopulated because of HPAI, a new flock needs hatch and reach maturity before it can produce eggs. This process takes approximately 4.5 to 6 months (USDA-ERS, 2023b. For HPAI impacting layer flocks, this biological constraint implies that the supply chain adjustment is a 6-month rolling total. This means it takes 6 months to replace a layer flock depopulated because of HPAI and each successive outbreak is additive. This adjustment rule is only relevant for layers. For an HPAI event the predominately impacts pullet farms, the adjustment would be shorter. Based on this biological constraint, we assume the supply chain will take six months to adjust to an HPAI outbreak. We call these specifications cumulative biological effects (impacts). The first biological effect variable, denoted $CBFlocks_t$, sums up the number of previously infected flocks over a 6-month period. This period reflects the biological cycle from when a chicken is hatched to when it starts laying eggs as a commercial lyer, which is approximately 6 months according to the USDA-ERS (2023b). Therefore, $CBFlocks_t$ represents the cumulative count of infected flocks over a 26-week timeframe, accounting for the biological growth cycle of replacement flocks. The second variable, $CBBirds_t$, similarly sums up the total number of HPAI cases over the same 26-week period. By considering the number of cases instead of the number of flocks, this variable accounts for the total number of birds impacted, thus incorporating the size of each flock. These two variables allow us to model the recovery and adjustment period in the supply chain due to HPAI's impact on egg production.

3.3. Consumer surplus changes

Changes in consumer surplus from the 2022 HPAI event based on the six HPAI specifications are computed to show that egg supply chain misspecification to provide economic context to econometric results. To what extent do different specifications for an HPAI result in different estimates for the change in consumer surplus? Procedures are based on Malone and Lusk (2016). Fig. 2 is a simple model of the U.S. retail egg market. We treat HPAI as a supply-side shock to the retail egg market, shifting the supply curve from S to S'. An HPAI outbreak results in higher retail egg prices and lower per capita availability of shell eggs (USDA-ERS, 2023a). The shift in the supply curve following HPAI increases egg

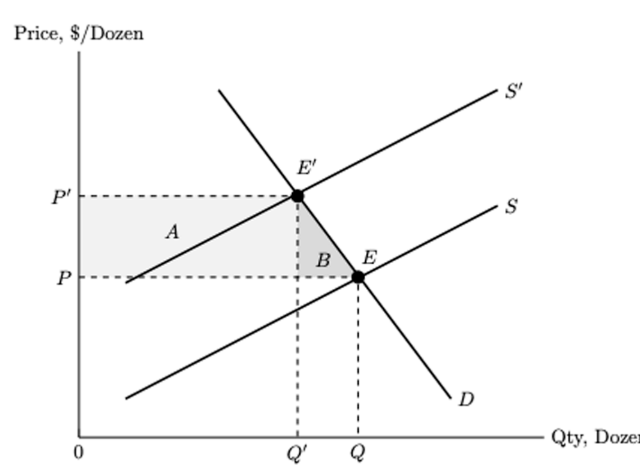

Fig. 2. Supply shock to the retail egg market from high path avian influenza.

prices from P to P' and decreases egg quantity from Q to Q'. The area given by $A + B$ is the change in consumer surplus resulting from HPAI.

The area in Fig. 2, given by $A + B$ is calculated with:

$$\Delta CS = ((P_t{'} - P_t) \times Q_t{'}) + 0.5((P_t{'} - P_t) \times (Q_t - Q_t{'})). \quad (2)$$

In Eq. (1), β_1 gives the percent change in retail egg prices for an increase in the number of HPAI outbreaks or birds impacted by HPAI. Using observed values for $HPAI_t$, we can calculate the percent change in egg prices using Eq. (1), denoted by $\%\Delta P_t$. The percent change in price is translated into percentage changes in quantity using own-price elasticities of demand for retail eggs from the literature (Andreyeva et al., 2010; Okrent and Alston, 2011; Bakhtavoryan et al., 2021).[2] The percent change in quantity is given by $\%\Delta Q = \%\Delta P \times E$ where E is the own-price elasticity of demand for eggs taken from the literature and $\%\Delta Q$ is the percent change in egg quantity. Using 2021 pre-HPAI values for P and Q, we calculate $Q' = (1 + \%\Delta Q) \times Q$ and $P' = (1 + \%\Delta P) \times P$. Together, this gives us all relevant information to calculate ΔCS in Eq. (2).

4. Data

The primary focus of this analysis is retail table egg prices, specifically examining their behavior before, during, and after an HPAI outbreak. To accomplish this task, we collect weekly regional egg price data from USDA's AMS from January 7, 2022, through June 16, 2023 (USDA-AMS, 2023). Note that the first case of HPAI in a commercial egg operation for the most recent disease event was February 22, 2022, and the last was December 20, 2022. Egg price data from USDA-AMS are for six U.S. regions and reflect an average across grocery stores surveyed each week in those regions. Descriptions of these regions are in Table 1.

In the data, egg characteristics include *Quality*, *Color*, *Size*, and *Container*. Quality grade and size refer to USDA's shell egg grading standards. Regional differences are controlled for with binary variables denoting each region in the USDA-AMS retail price reports (*Region*). Monthly binary variables control for seasonality (*Month*). We include the Prices Paid Index for Commodities and Services, Interest, Taxes, and Farm Wage Rates (PPITW) as a continuous control variable in the models to control for other factors unrelated to HPAI that could inflate egg prices. Data for PPITW is collected from USDA-NASS. We control for consumer awareness about HPAI using a Google Trends Index. The base for the index is January 2021 and includes the terms "bird flu", "HPAI", and "Avian Influenza". The includes the terms Avian Influenza, Bird Flu, and HPAI. Descriptions of these variables and their levels are in Table 1.

The mechanism through which HPAI impacts egg prices is the birds and flocks destroyed to control the disease. These birds (flocks) that are depopulated impact egg production which impacts prices. The problem is that egg prices and quantities could be simultaneously determined, so egg production is an endogenous variable and will not provide the impacts of HPAI on egg prices. However, our approach, which measures the number of birds (flocks) depopulated, captures the exogenous variation in egg production related to HPAI. Moreover, we can recover egg production by making assumptions about production per bird. We could not recover the birds impacted by HPAI if We worked backwards using egg production because many factors are impacting production

Using data on the number of birds and flocks impacted by HPAI gives a more precise measure of the amount of egg production affected by HPAI. Including egg quantities in a model would be redundant. As a simple example, assume that one bird is depopulated because of HPAI. The egg supply chain does not have excess capacity of layers, so it will take 6 months for that bird to be replaced. Commercial layers will produce approximately 285 eggs annually (24 per month). So, the lost production of eggs from HPAI in this example is 1 bird × 24 eggs × 6 months = 144 eggs. Our HPAI variables precisely measure the decline in egg production if we assume a constant rate of production per bird. Egg quantities would provide an imprecise measure of the impacts of HPAI because many factors impact egg production. Moreover, we must make strict assumptions about how much production is substituted between table egg and breaker egg production because there is no data on this substitutability. Finally, to our knowledge, there is no data on retail egg quantities. However, the USDA-NASS Chicken and Egg report contains data on egg production, and our variables directly measure the decline in that report's production.

Table 1
Variable names and description.

Variable Name	Description
Price	Weekly weighted average retail egg prices ($ per dozen) in nominal dollars
Birds	Number of birds impacted by HPAI (millions of birds)
Flocks (0,1)	= 1 if HPAI outbreak occurred during a given week; 0 otherwise
CBirds	Cumulative number of birds impacted by HPAI (millions of birds)
Cflocks	Cumulative number of flocks impacted by HPAI (millions of birds)
CBBirds	6-month rolling sum of birds impacted by HPAI (millions of birds)
CBFlocks	6-month rolling sum of HPAI outbreaks
Color (0, 1)	Shell egg color = 1 if white; 0 otherwise
Size (0,1)	Three binary variables for shell egg weight class *Medium* (0,1) = 1 if medium; 0 otherwise *Large* (0,1) = 1 if large; 0 otherwise *Extra Large* (0,1) = 1 if extra large; 0 otherwise
Quality (0,1)	Six binary variables for shell egg quality grades and other quality characteristics *A* (0,1) = 1 if grade A; 0 otherwise *AA* (0,1) = 1 if grade AA; 0 otherwise *Organic* = 1 if organic; 0 otherwise *Vegetarian Fed* (0,1) = 1 if vegetarian fed; 0 otherwise *Cage-Free (0,1)* = 1 if cage-free; 0 otherwise *Omega-3* (0,1) = 1 if omega-3; 0 otherwise
Container (0,1)	Three binary variables for shell egg carton size *Doz* (0,1) = 1 if 1 dozen; 0 otherwise *1.5 Doz* (0,1) = 1 if 1.5 dozen; 0 otherwise *2.5 Doz* (0,1) = 1 if 2.5 dozen; 0 otherwise
Month (0,1)	Seasonal binary variables (April reference)
PPITW	Prices Paid Index for Commodities and Services, Interest, Taxes, and Farm Wage Rates (base = 2011).
Google Index	U.S. Composite Google Trends Index for Avian Influenza, Bird Flu, and HPAI. Base = Jan-21.

We measure the impacts of HPAI using data for 2022–2023 HPAI cases from the USDA Animal and Plant Health Inspection Service's HPAI Dashboard (USDA-APHIS, 2023). HPAI cases are reported by day, operation type, state, and county. The operations we focus on in this analysis include table egg layers. HPAI also impacted breeder and pullet farms, but those operations follow a different biological lag, and our central assumption of six months would not work. Each observation reflects a specific confirmation of HPAI in a commercial flock and reports the number of birds on that operation impacted by the disease, so our estimations consider the number of flocks and birds affected by HPAI in each region.

To construct the lagged HPAI variables, we assume it takes six months from when the HPAI outbreak is detected and reported by USDA-APHIS. This assumption is driven by data availability. We know when USDA reports that disease detection. We do not know whether the grower and integrator knew about HPAI before USDA reported it, which could imply that the supply chain may begin adjusting before the disease is officially reported and the flock is depopulated.

Table 2 summarizes HPAI cases by flock type (USDA-APHIS, 2023). In our sample, there were 43.29 million cases of HPAI in layer operations. This is approximately 97 percent of cases impacting the egg supply

[2] Note that using own-price elasticities of demand for welfare analysis does not indicate a violation of our identification assumptions, which says that HPAI is not a demand shock. HPAI is a supply shock. Understanding the price-quantity relationship given by an own-price elasticity of demand allows us to quantify movement along the demand curve following a shift in supply from HPAI.

Table 2
Summary of HPAI Cases by Flock Type, Jan 2021-Dec 2023.

Flock Type	HPAI Cases (Mil. Birds)
Egg Breeder HPAI Cases	0.12
Egg Layer HPAI Cases	56.17
Egg Pullets HPAI Cases	2.53
Total HPAI Cases	58.52

Note: HPAI cases is the number of birds impacted.

chain during that time. Two of the HPAI variable specifications include a 6-month rolling total, which reflects the adjustment to an HPAI outbreak—the 6-month biological constraint to replace a depopulated flock of layers. These specifications are only relevant for layer operations. The HPAI data does include cases for breeders and pullets, but these cases are such a small percentage of the total, so removing them would not significantly change our results. If HPAI cases were more evenly distributed across flock types, then it would be more appropriate to create separate HPAI variables for each flock type that include different biological lags, which accurately flocked to the life cycle stage when HPAI impacted those birds.

Table 3 presents a another summary national HPAI outbreaks and the impact on average retail egg prices from January 2021 to June 2023. The table reports the total number of HPAI cases, outbreaks, and cases per outbreak. The 2022 HPAI event impacted 44.43 million birds on commercial egg operations, which reflects approximately 14.5 percent of January 1 layer inventories (USDA-NASS, 2023). There were 37 HPAI outbreaks with an average flock size of 1.2 million birds (Table 3). During the HPAI outbreak, average retail egg prices increased from \$2.34/dozen to \$3.04/dozen or 30 percent. Post-HPAI increased 45 percent from pre-HPAI levels. This suggests that the impact of HPAI on egg prices does not dissipate immediately after an outbreak. Instead, the effect is longer lasting, which provides preliminary evidence for our argument of biological lags. Without controlling for other supply shocks and sources of inflation, it would not be appropriate to attribute all of the increase in egg prices to HPAI.

5. Results

In this section, we present results to show how misspecification of the egg supply chain can lead to misleading and, perhaps, incorrect results about the effects of HPAI on retail egg prices. First, we discuss regression results for the linear models that include different specifications for HPAI during the 2022–2023 disease event. Comparisons are made among the different specifications. We extend our analysis to regional egg market, providing a more nuanced discussion of HPAI impacts and the implications for consumer welfare. This provides transition for the next section which extends model results to an analysis of consumer welfare.

Table 3
Summary of HPAI outbreaks in layer operations and retail egg prices, January 2021 – Dec 2023.

	National
Birds (mil.)	58.52
Flocks	55.00
Birds per Flock (mil.)	1.07
Egg Price (\$/dz.)	
Pre HPAI[a]	2.34
During HPAI[b]	3.01
Post HPAI[c]	3.24

[a] Average retail egg price before the first HPAI outbreak on February 22, 2022.
[b] Average retail egg price between first HPAI outbreak on February 22, 2022 and last HPAI outbreak on December 22, 2023.
[c] Average retail egg price after HPAI outbreak on December 22, 2022. There were outbreaks in November 2023. Retail prices were not included in post HPAI averages.

Before moving to the econometric results, Fig. 3 plots national weekly average egg prices against the four HPAI specifications incorporating cumulative effects. The variables in the top panel measure the number of HPAI cases, and the bottom panel measures the number of outbreaks. In both cases, Fig. 3 illustrates how, without a biological lag, the cumulative variables do not capture the post-outbreak decline in egg prices. This implies that *Cflocks* and *Cbirds* could overestimate the impacts of HPAI on egg prices and require a decision ex-post about when cumulative impacts stop affecting egg prices.

5.1. Econometric results

It takes approximately 4.5 to 6 months to replace a flock that is depopulated because of HPAI (USDA-ERS, 2023b. Two of our variable specifications consider this lagged adjustment, CBBirds and CBFlocks. We consider 4, 5, and 6 months for lag lengths and base our lag selection on r-squared, Akaike information criterion, and Bayesian information criterion. Results for the three lag lengths are reported in Table A.1. Each of the three criteria selects a 6-month lag length. We use a 6-month lag for the remainder of the models and results discussion.

Table 4 presents results from our models that measure the impacts of HPAI with the number of confirmed HPAI cases (birds). Estimates for *Birds*, one of the variables that measure HPAI as a single-week impact, shows that egg prices decrease by 3.6% when HPAI infections increase by 1 million birds. Estimates for C**b**irds show that cumulatively, as the number of HPAI cases increases by 1 million, retail egg prices increase by 0.60%. Incorporating biology with a six-month lag, the estimate for CBBirds says that egg prices increase 0.30% when the number of HPAI cases during the previous six months increases by one million. Findings

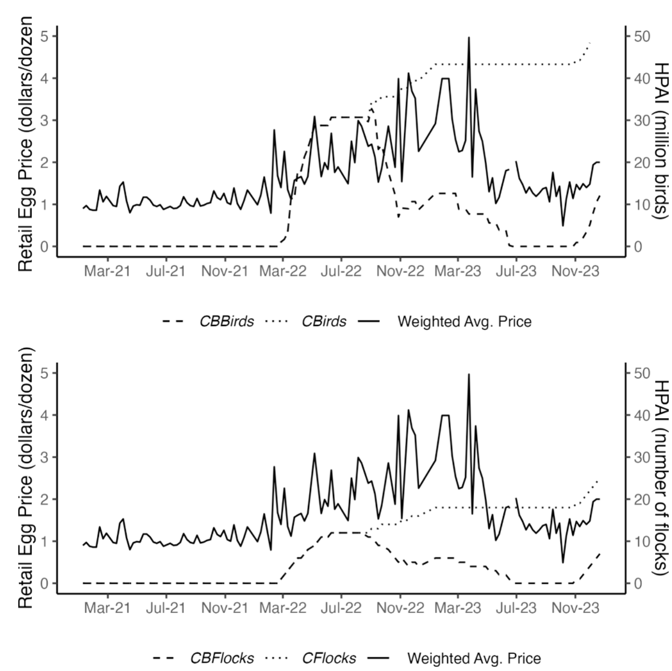

Fig. 3. National retail egg prices (large, grade A, dozen) and constructed cumulative HPAI variables, Jan 2021 – Dec 2023. Weighted Avg. Price is the national weighted average price of retail eggs (large, grade A, dozen). CBBirds is a 6-month rolling total of the number of birds depopulated because of HPAI (million birds). CBirds is the cumulative number of birds depopulated because of HPAI (million birds). CBFlocks is a 6-month rolling total of HPAI outbreaks (flocks). CFlocks is the cumulative number of HPAI outbreaks. **Source:** U.S. Department of Agriculture's Agricultural Marketing Service and Animal and Plant Inspection Service.

Table 4
The effects of HPAI on logged retail egg prices Jan 2021-Dec 2023 (million birds).

Variable	(1) Estimate	(1) Robust Std. Error	(2) Estimate	(2) Robust Std. Error	(3) Estimate	(3) Robust Std. Error
Intercept	-0.865^{***}	(0.133)	0.280	(0.198)	-1.042^{***}	(0.123)
$CBBirds_{it}$	0.003^{***}	(0.001)				
$CBirds_{it}$			0.006^{***}	(0.001)		
$Birds_{it}$					-0.036^{***}	(0.007)
Number of obs.	1,510		1,510		1,510	
R-Squared	0.576		0.588		0.581	
AIC	558.7		514.4		540.7	
BIC	686.3		642.1		668.4	

Note: *$P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$. Control variables are omitted for brevity but include egg color, egg grade, egg size, container size, Producer Prices Paid Index, Google Index, and seasonality. *PPITW* base is 2011 and *Google Index* base is January 2021.

highlight the importance of considering both the biological time frame and the specific flock sizes impacted by HPAI in understanding the potential effects on egg prices.

Table 5 presents results from our regressions that measure the number of confirmed HPAI outbreaks (flocks). The coefficient estimate for *Flocks* says that egg prices decrease during an HPAI outbreak. This is an important finding because *Flocks* treats each HPAI outbreak as a discrete event. As described in Section 3, Flocks is a specification that lends itself to an event study. This implies that a misspecified event study might misrepresent the impacts of HPAI on egg prices. Estimates for Cflocks show that as the number of HPAI outbreaks increases by one million, retail egg prices increase by 1.29%. Incorporating a six-month lag, the estimate for *CBFlocks* indicates that egg prices rise 1.09% when the number of flocks infected with HPAI during the previous six months increases by one million. These findings provide another example illustrating the importance of appropriately modeling the supply chain under consideration. However, these specifications ignore the size of flocks impacted by HPAI. All three specifications treat outbreaks same regarding egg price impacts, meaning the models are estimating the average flock size. While providing important information this may be harder to extend to future outbreaks if there are structural changes in the industry that lead to higher concentration of birds on a premises, i.e., larger average flock sizes.

For context, in 2022–2023, there were 55 commercial egg layer flocks, or 58.52 million birds, affected by HPAI. One million birds affected by HPAI reflect 1.7% of total HPAI infections, and one flock reflects 1.8% of total layer flocks impacted by HPAI. Results that ignore biology tend to overestimate the effects of HPAI on egg prices. One explanation is that these variables cannot capture the post-outbreak decline in egg prices (Fig. 3). By design, *Cflocks* and *Cbirds* remain constant even after egg prices decline post-outbreak. *CBFlocks* and *CBBirds* return to zero six months after the last outbreak. The difference allows for a nuanced estimation of how the egg industry may return to normal post outbreak. By allowing for the gradual, biologically feasible timed resupply of birds it avoids the immediate discontinuity of the purely cumulative measurement with the total impact.

5.2. Regional impacts

The main analysis of this paper examines how HPAI impacts national retail egg prices. The analysis uses weekly average egg prices from USDA-AMS and weekly bird and flock totals for HPAI detections from USDA-APHIS. The results reported in Tables 4 and 5 provide an average effect on the aggregate retail egg market. These results align with the paper's main theme that misspecification of the egg supply chain can bias results and be magnified in policy analysis. A more nuanced discussion of the effects of HPAI on retail egg prices would acknowledge the regionality of egg markets and the spatial spread of disease. This section extends the main results by determining how region-specific HPAI outbreaks impact regional egg prices.

USDA-AMS reports weekly retail egg prices for six regional egg markets. These regional markets include Midwest (IA, IL, IN, KY, MI, MN, ND, NE, OH, SD, WI); Northeast (CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT); Northwest (ID, MT, OR, WA, WY); South Central (AR, CO, KS, LA, MO, NM, OK, TX); Southeast (AL, FL, GA, MS, NC, SC, TN, VA, WV); and Southwest (AZ, CA, NV, UT). USDA-APHIS reports daily HPAI detections, including flock type and number of birds impacted at the county level. The HPAI data from USDA-APHIS was regionally aggregated to match the regional egg markets defined by USDA-AMS. *CBBirds* and *CBFlocks* were constructed for each region.

Table A.2 in the appendix summarizes regional egg prices, HPAI outbreaks, and cases. The table shows average egg prices for three periods: pre-HPAI, HPAI, and post-HPAI, where post-HPAI is defined as the period immediately following the outbreak on June 16, 2023.[3] USDA-ERS (2023a) analyzes wholesale egg prices and quantities during HPAI. Table A.2 reports regional HPAI numbers, which effectively capture changes to quantities if an assumption were made about egg production per layer per week. For each region, egg prices continue to increase following the last HPAI outbreak, which provides nonparametric evidence to our main argument that there is a lagged adjustment process following an HPAI outbreak. Notice that there were no outbreaks in the southeast or southwest, but prices increased in those regions just the same. This suggests there might be regional spillovers of HPAI outbreaks across regions. However, as we describe in Section 3, there are several confounding factors related to inflation that could increase regional egg prices regardless of whether an HPAI outbreak occurred.

The following panel regression provides a crude test for regional effects of HPAI:

$$\widetilde{Price}_{irt} = \beta_{0r} + \beta_{1r}HPAI_{rt} + \gamma X_{irt} + \theta R_r + \delta Z_t + \varepsilon_{irt}, \quad (3)$$

where r is an index for region, $HPAI_{rt}$ is a vector that measures HPAI in region r,R_r are regional effects, and all remaining items are as previously defined. In Eq. (3), β_{1r} is the effect of region r HPAI outbreaks (cases) on region r egg prices and β_{2r} is vector of effects for HPAI outbreaks (cases) in regions $-r$ on region r egg prices. In these models, we focus on the two HPAI specifications that incorporate a cumulative effect with a six-month biological lag, *CBBirds* and *CBFlocks*.

Results for the regional model are in Table A.3. The regional model offers several interesting insights. Regional egg prices increase by 15.2% when cumulative HPAI cases increase by one million in the Northwest (Table A.3). A million bird increase in HPAI in the Midwest and South Central increases regional egg prices by 1.0% and 5.4%, respectively. The direction of the impact is not consistent across regions. Increases in HPAI cases in the Northeast and Southwest decrease regional egg prices.

[3] There were outbreaks in November and December 2023. For illustrative purposes, these outbreaks were omitted from calculating price averages during the three phases: pre-, during-, and post-outbreak. The data for estimating regression models includes November and December 2023 outbreaks.

Table 5
The effects of HPAI on logged retail egg prices Jan 2021-Dec 2023 (flocks).

Variable	(1) Estimate	(1) Robust Std. Error	(2) Estimate	(2) Robust Std. Error	(3) Estimate	(3) Robust Std. Error
Intercept	-0.765^{***}	(0.137)	0.160	(0.196)	-1.089^{***}	(0.126)
$CBFlocks_{it}$	0.011^{***}	(0.003)				
$CFlocks_{it}$			0.013^{***}	(0.002)		
$Flocks_{it}(0,1)$					-0.099^{***}	(0.028)
Number of obs.	1,510		1,510		1,510	
R-Squared	0.578		0.587		0.577	
AIC	549.7		520.1		554.9	
BIC	677.4		647.7		682.6	

Note: *P < 0.1; **P < 0.05; ***P < 0.01. Control variables are omitted for brevity but include egg color, egg grade, egg size, container size, Producer Prices Paid Index, Google Index, and seasonality. *PPITW* base is 2011 and *Google Index* base is January 2021.

Overall, results provide evidence of regional impacts on retail egg prices.

Findings are similar for regional HPAI variables that measure the impacts of the disease with the number of depopulated flocks. HPAI outbreaks in South Central consistently impact egg prices across regions. Retail egg prices increase by 4.6% and 8.5% when the cumulative number of HPAI outbreaks increases by one in the Midwest and South Central regions, respectively. Findings show that some regonal HPAI outbreaks decreases egg prices in other regions. Specifically, we find outbreaks in the Northeast and Southwst decrease retail egg prices.

One potential drawback with the regional data is that these are USDA-defined regions. USDA may have defined these regions for data collection or data reporting purposes. That does not mean that egg supply chains operate in ways consistent with USDA's regional definitions. HPAI certainly does not obey regional definitions. Future work could explore regional HPAI dynamics and potential trade flows of eggs across regions.

5.3. Robustness

Our results depend on whether we appropriately control for two important factors relating to HPAI that also impact retail egg prices. The first control variable that is important for our analysis is inflation. In Section 3.1, we provide context for why inflation is an important consideration. Namely, it could bias our results upward because our HPAI specifications would measure all sources of egg price inflation. We also discuss why the CPI is an inappropriate control for inflation in Section 3.1. In Table A.4, we show what happens to estimates for the two main HPAI specifications when we ignore inflation and control for inflation using the CPI and PPITW indices. Ignoring inflation as a control variable, our estimate for *CBBirds* is 0.87%. Our estimate for *CBBirds* declines from 0.87% to 0.58% and 0.30% when we use CPI and PPITW as controls for inflation, respectively. Similarly, our estimate for *CBFlocks* is 2.7% when we ignore inflation. Controlling for inflation using CPI and PPITW, the estimate for *CBFlocks* changes to 1.7% and 1.1%, respectively. Ignoring inflation and controlling for inflation using the CPI results in us overestimating the impacts of HPAI on retail egg prices.

The second control variable that is important for our analysis is consumer demand. In Section 3.1, we argue why consumer demand impacts through food recalls is not a concern. However, there are mixed findings about whether consumer awareness about HPAI could impact consumer egg purchasing. We construct a composite U.S. Google Trends Index (base = Jan-21) for Avian Influenza, Bird Flu, and HPAI to control for consumer awareness about HPAI. Results in Table A.5 show how our estimates change when we omit our Google Trend Index as a control variable. That is, estimates for *CBBirds* and *CBFlocks* are smaller when we do not include a control variable for consumer awareness. This finding is expected. The extent to which consumer awareness impacts purchasing decisions would lower retail egg prices. So, omitting a variable for consumer awareness would result in us underestimating the impacts of HPAI as a supply shock.

6. Policy implications

Results have important policy implications for accurately quantifying consumer welfare losses from HPAI and higher egg prices. Table 6 presents the average marginal change in price and quantity demand changes for retail eggs. We use observed values for the six HPAI specifications to estimate the average marginal percentage change in national retail egg prices from February 2022 to December 2023. Estimates in Table 6 are the average weekly percent change in retail egg prices during the 2022–2023 HPAI event. *CBBirds* and *CBFlocks* estimate that prices increased by 5.30% and 5.34% from HPAI during 2022–2023. The single-week variables estimate weekly egg price changes of −2.76% and −3.05% for *Birds* and *Flocks*, respectively. Price changes from Table 6 and own-price elasticities of demand are used to calculate the percent change in quantity demand for eggs.

Own-price elasticities are taken from Andreyeva et al.(2010), Okrent and Alston (2011), and Bakhtavoryan et al. (2021), which are −0.27, −0.18, and −0.23, respectively. Using the six HPAI variables and three own-price elasticities, Table 7 reports 18 estimates for the percent change in quantity demand for retail eggs. Variable construction makes this an expected result because Cbirds and Cflocks do not decline after six months when impacted flocks are replaced. By comparison, CBBirds and CBFlocks account for the post event supply chain restocking that the other specifications ignore. So, a smaller effect size is expected relative to Cbirds and Cflocks. In contrast, Birds and Flockss estimate increased retail egg quantities during an HPAI event, further highlighting how misspecification leads to biased results, even if that bias appears obvious to those familiar with the industry.

Estimates in Table 6 are used to calculate changes in consumer surplus (CS). Per capita egg consumption and egg prices from 2021 are used as pre-HPAI values for CS calculations in Eq. (2). Based on marginal price changes, ranging from 20.79% to −3.05%, during the 2022–2023 HPAI event, retail egg prices changed from $2.34 per dozen to $2.27–$2.83 per dozen. Note *Birds* and *Flocks* estimates a decline in egg prices. Using 2021 values, the U.S. population of 332.14 million consumes 201 eggs per person annually, the quantity demanded for eggs totaled 5.578 billion dozen eggs before HPAI (USDA-ERS, 2023c). Across six HPAI variable specifications and three own-price elasticities of demand, we estimate that during the 2022–2023 HPAI event, quantity demanded for eggs changed to 5.27–5.63 billion dozen eggs.

Table 7 reports estimates for the change in consumer surplus during 2022–2023 HPAI. When biological lags are considered, we estimate a loss of consumer surplus between $687 and $693 million. *Cbirds* and *Cflocks* estimate losses in consumer surplus between $2.369 and $2.663 billion. On average, *Cbirds* and *Cflocks* overestimate consumer surplus changes by a factor of 7 and 5, respectively. This result is expected because *Cbirds* and *Cflocks* do not consider the biological lag to replace impacted flocks. *Birds* and *Flocks* estimate consumer surplus gains,

Table 6
Estimated changes in weekly retail egg prices and quantity demanded for eggs from 2022 to 2023 HPAI outbreaks.

	CBBirds	*Cbirds*	*Birds*	*CBFlocks*	*Cflocks*	*Flocks*
%Δ*Price*	5.30%	20.79%	−2.76%	5.34%	18.61%	−3.05%
%Δ$Quantity_1$ [a]	−0.95%	−3.74%	0.50%	−0.96%	−3.35%	0.55%
%Δ$Quantity_2$ [b]	−1.43%	−5.61%	0.74%	−1.44%	−5.03%	0.82%
%Δ$Quantity_3$ [c]	−1.24%	−4.88%	0.65%	−1.25%	−4.37%	0.72%

[a]Uses −0.18 as the own-price elasticity of demand from Okrent and Alston (2011).
[b] Uses −0.27 as the own-price elasticity of demand from Andreyeva et al. (2010).
[c] Uses −0.23 as the own-price elasticity of demand from Bakhtavoryan et al. (2021).

Table 7
Changes in consumer surplus from 2022 HPAI outbreak for different HPAI variable specifications (million dollars).

	Change in Consumer Surplus					
Own-Price Elasticity	*CBBirds*	*Cbirds*	*Birds*	*CBFlocks*	*Cflocks*	*Flocks*
Okrent and Alston (2011)[a]	−688.56	−2,663.03	360.99	−693.48	−2,388.86	399.51
Andreyeva et al. (2010) [b]	−686.91	−2,637.64	361.44	−691.81	−2,368.52	400.06
Bakhtavoryan et al. (2021)[c]	−687.56	−2,647.57	361.26	−692.46	−2,376.47	399.84

[a]The own-price elasticity of demand from Okrent and Alston (2011) is −0.18.
[b] The own-price elasticity of demand from Andreyeva et al. (2010) is −0.27.
[c] The own-price elasticity of demand from et al. (2021) is −0.23.

highlighting how misspecification can introduce bias into poliy relevant estimates.

7. Conclusion

The dynamics of biological production lags underscore the interconnectedness of agri-food supply chains and the need for models to capture these relationships accurately. In the case of HPAI, retail egg price fluctuations underscore the interplay between biological disruptions and economic indicators. Our study builds on applied economics literature to showcase the significant implications of HPAI on retail egg prices. With the 2022–2023 HPAI as our focal event, we have highlighted that a misspecification of the egg supply chain can lead to skewed perceptions, often understating or biasing the real impact of such biological disturbances.

Our findings reveal a pivotal aspect of econometric modeling—the inherent need for accurate specification of agricultural production biology—especially in the context of external shocks like disease outbreaks, cannot be overstated. When we contrast different models based on the number of birds and flocks affected by HPAI, incorporating biological lags in our analyses provides a more accurate reflection of price impacts. Indeed, when biological timelines are integrated, the results offer a more accurate, nuanced insight into retail egg market dynamics. By understanding biological lags in production systems, agri-food researchers improve their econometric precision and pave the way for informed policy decisions that factor in the intricacies of the food supply chain.

A clear understanding of the true economic significance and impact on consumer surplus can guide policymakers in valuing and devising proactive disease monitoring and control as well as responsive measures to mitigate the repercussions of such business disrupting events. When we extend these results to consumer surplus, we find that models that ignore the cumulative nature of HPAI estimate gains in consumer surplus, and models that ignore the post-outbreak recovery of layer inventories overestimate the consumer surplus loss by a factor of 3 to 4. This information could be invaluable for policymakers to preemptively structure compensatory mechanisms, subsidy schemes, or other supportive measures to avoid the disruptions and for affected stakeholders in the supply chain.

Econometrically, this study's findings emphasize the potential pitfalls of oversight or simplification in modeling. This paper emphasizes the value of precision for biosecurity policy to manage infectious animal disease (Hennessy and Rault, 2023). The discrepancy between single-week variables and those accounting for biological lags elucidates the potential biases that can arise, even unintentionally, leading to results that can misguide or misinform. It is a potent reminder for researchers to constantly align their models with the innate characteristics and timelines of the systems they seek to study.

Future research could expand in several directions. One evident path is to explore the broader impacts of disease outbreaks on interconnected food systems and not just retail prices such as food service and processing. How does an outbreak in one segment influence the broader agri-food landscape? How do consumers' perceptions, zoonosis risk avoidance, and behavior alter in response to such shocks over time and are the additive impacts rather than direct impacts from one specific event? Additionally, diving deeper into the nuances of biological lags, and potentially other overlooked dynamics, could yield even more refined models. This study underscores a critical aspect of food supply chain modeling. The next steps lie in broadening this understanding and translating it into actionable insights for both the industry and policymakers.

CRediT authorship contribution statement

James L. Mitchell: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Jada M. Thompson:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Trey Malone:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Appendix

Table A.1
The effects of HPAI on logged retail egg prices using different HPAI variable specifications and lag lengths Jan 2021-Dec 2023.

	Lag Length					
	6 months	5 months	4 months	6 months	5 months	4 months
Intercept	−0.865***	−0.901***	−0.988***	−0.765***	−0.832***	−0.922***
	(0.133)	(0.132)	(0.129)	(0.137)	(0.135)	(0.132)
$CBBirds_{it}$	0.003***	0.003***	0.001			
	(0.001)	(0.001)	(0.001)			
$CBFlocks_{it}$				0.011***	0.010***	0.007**
				(0.003)	(0.003)	(0.004)
Number of obs.	1,510	1,510	1,510	1,510	1,510	1,510
R-Squared	0.576	0.575	0.573	0.578	0.577	0.575
AIC	558.7	561.5	567.4	549.7	556.2	563.6
BIC	686.3	689.2	695.1	677.4	683.9	691.3

Note: *P < 0.1; **P < 0.05; ***P < 0.01. *CBBirds* measures HPAI in millions of birds. *CBFlocks* measures HPAI in flocks of birds. Seasonal coefficient estimates are omitted to save space. Control variables are omitted for brevity but include egg color, egg grade, egg size, container size, Producer Prices Paid Index, Google Index, and seasonality. *PPITW* base is 2011 and *Google Index* base is January 2021.

Table A.2
Regional summary of HPAI outbreaks and retail egg prices, January 2021 – June 2023.

	National	Midwest	Northeast	Northwest	South Central	Southeast	Southwest
Birds (mil.)	56.17	36.75	6.20	1.02	7.48	0	4.71
Flocks	26	16	8	1	7	0	6
Flock Size (mil.)	2.60	2.30	0.78	1.02	1.07	0	0.79
Egg Price ($/dz.)							
Pre HPAI[a]	2.34	2.06	2.53	2.10	2.15	2.38	2.42
During HPAI[b]	3.01	2.71	3.19	2.69	2.77	2.93	3.46
Post HPAI[c]	3.24	2.68	3.30	3.02	2.90	3.29	3.13

[a]Average retail egg price before the first HPAI outbreak on February 22, 2022.
[b]Average retail egg price between first HPAI outbreak on February 22, 2022 and last HPAI outbreak on December 22, 2023.
[c]Average retail egg price after last HPAI outbreak on December 22, 2022.

Table A.3
The effects of regional HPAI cases (birds) on regional egg prices, Jan 2021-Dec 2023.

	(1) Estimate	(1) Robust Std. Error	(2) Estimate	(2) Robust Std. Error
(Intercept)	−0.608***	0.080	−0.556***	0.081
$CBBirds^{NE}$	−0.031***	0.007		
$CBBirds^{MW}$	0.010***	0.002		
$CBBirds^{SC}$	0.054***	0.008		
$CBBirds^{NW}$	0.152***	0.035		
$CBBirds^{SW}$	−0.048**	0.019		
$CBFlocks^{NE}$			−0.033***	0.005
$CBFlocks^{MW}$			0.046***	0.007
$CBFlocks^{SC}$			0.085***	0.012
$CBFlocks^{NW}$			−0.007	0.046
$CBFlocks^{SW}$			−0.088**	0.017
Number of obs.	4,056		4,056	
R-Squared	0.710		0.712	
AIC	433.3		413.9	
BIC	654.1		634.7	

Note: *CBBirds* measures HPAI in millions of birds. *CBFlocks* measures HPAI in flocks of birds. NE is northeast; MW is Midwest; NW is northwest; SC is south central; SE is southeast; SW is southwest. Control variables are omitted for brevity but include egg color, egg grade, egg size, container size, Producer Prices Paid Index, Google Index, regional fixed effects, and seasonality. P < 0.1; **P < 0.05; ***P < 0.01.

Table A.4
The effects of HPAI on logged retail egg prices Jan 2021-Dec 2023 using different control variables for egg price inflation.

	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	0.986***	−1.564***	−0.865***	0.995***	−1.439***	−0.765***
	(0.052)	(0.169)	(0.133)	(0.051)	(0.172)	(0.137)
$CBBirds_{it}$	0.009***	0.006***	0.003***			
	(0.001)	(0.001)	(0.001)			

(*continued on next page*)

Table A.4 (*continued*)

	(1)	(2)	(3)	(4)	(5)	(6)
$CBFlocks_{it}$				0.027***	0.017***	0.011***
				(0.003)	(0.003)	(0.003)
Color (0,1)	−0.116***	−0.142***	−0.137***	−0.117***	−0.142***	−0.136***
	(0.022)	(0.021)	(0.021)	(0.021)	(0.021)	(0.021)
Quality (0,1)						
AA	0.035	0.075**	0.070**	0.039	0.076**	0.070**
	(0.036)	(0.033)	(0.034)	(0.036)	(0.033)	(0.033)
Cage-Free	0.494***	0.479***	0.483***	0.493***	0.479***	0.483***
	(0.032)	(0.031)	(0.031)	(0.032)	(0.031)	(0.031)
Omega-3	0.547***	0.547***	0.549***	0.547***	0.547***	0.549***
	(0.029)	(0.027)	(0.027)	(0.028)	(0.027)	(0.027)
Organic	0.888***	0.882***	0.887***	0.889***	0.883***	0.888***
	(0.036)	(0.035)	(0.036)	(0.036)	(0.035)	(0.036)
Veg-Fed	0.441***	0.454***	0.458***	0.443***	0.455***	0.458***
	(0.037)	(0.036)	(0.036)	(0.037)	(0.036)	(0.036)
Size (0,1)						
Large	−0.139***	−0.169***	−0.164***	−0.142***	−0.169***	−0.164***
	(0.022)	(0.021)	(0.021)	(0.022)	(0.021)	(0.021)
Container (0.1)						
Doz.	−0.374***	−0.378***	−0.380***	−0.377***	−0.380***	−0.381***
	(0.035)	(0.032)	(0.032)	(0.035)	(0.032)	(0.032)
Google Index	0.000	0.000***	0.000***	0.000	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
CPI		0.010***			0.009***	
		(0.001)			(0.001)	
PPITW			0.016***			0.015***
			(0.001)			(0.001)
Number of obs.	1,510	1,510	1,510	1,510	1,510	1,510
R-Squared	0.513	0.582	0.576	0.525	0.585	0.578
AIC	766.7	538.0	558.7	728.3	524.4	549.7
BIC	889.0	665.7	686.3	850.7	652.1	677.4

Note: *P < 0.1; **P < 0.05; ***P < 0.01. Seasonal coefficient estimates are omitted to save space. There were no observations for medium sized eggs or eggs sold in 2.5 dozen containers in the data for national egg prices. Column labels denote results for separate estimations. *CPI* base is 1982–84, *PPITW* base is 2011, and *Google Index* base is January 2021.

Table A.5
The effects of HPAI on logged retail egg prices Jan 2021-Dec 2023 and the sensitivity of results to controlling for consumer awareness using a Google Trends Index.

	(1)	(2)	(3)	(4)
Intercept	−0.865***	−0.678***	−0.765***	−0.567***
	(0.133)	(0.125)	(0.137)	(0.129)
$CBBirds_{it}$	0.003***	0.002*		
	(0.001)	(0.001)		
$CBFlocks_{it}$			0.011***	0.008***
			(0.003)	(0.003)
Color (0,1)	−0.137***	−0.135***	−0.136***	−0.134***
	(0.021)	(0.021)	(0.021)	(0.021)
Quality (0,1)				
AA	0.070**	0.067**	0.070**	0.066*
	(0.034)	(0.034)	(0.033)	(0.034)
Cage-Free	0.483***	0.483***	0.483***	0.483***
	(0.031)	(0.031)	(0.031)	(0.031)
Omega-3	0.549***	0.548***	0.549***	0.548***
	(0.027)	(0.027)	(0.027)	(0.027)
Organic	0.887***	0.884***	0.888***	0.885***
	(0.036)	(0.035)	(0.036)	(0.035)
Veg-Fed	0.458***	0.457***	0.458***	0.457***
	(0.036)	(0.036)	(0.036)	(0.036)
Size (0,1)				
Large	−0.164***	−0.161***	−0.164***	−0.161***
	(0.021)	(0.021)	(0.021)	(0.021)
Container (0.1)				
Doz.	−0.380***	−0.381***	−0.381***	−0.382***
	(0.032)	(0.033)	(0.032)	(0.033)
PPITW	0.016***	0.014***	0.015***	0.013***
	(0.001)	(0.001)	(0.001)	(0.001)
Google Index	0.000***		0.000***	
	(0.000)		(0.000)	
Number of obs.	1,510	1,510	1,510	1,510
R-Squared	0.576	0.570	0.578	0.572

(*continued on next page*)

Table A.5 (*continued*)

	(1)	(2)	(3)	(4)
AIC	558.7	579.6	549.7	572.2
BIC	686.3	701.9	677.4	694.6

Note: *P < 0.1; **P < 0.05; ***P < 0.01. Seasonal coefficient estimates are omitted to save space. There were no observations for medium sized eggs or eggs sold in 2.5 dozen containers in the data for national egg prices. Column labels denote results for separate estimations. *CPI* base is 1982–84, *PPITW* base is 2011, and *Google Index* base is January 2021.

References

Acosta, A., Barrantes, C., Ihle, R., 2020. Animal disease outbreaks and food market price dynamics: evidence from regime-dependent modelling and connected scatterplots. Aust. J. Agric. Resour. Econ. 64 (3), 960–976.

Acosta, A., Lloyd, T., McCorriston, S., Lan, H., 2023. The ripple effect of animal disease outbreaks on food systems: the case of African Swine Fever on the Chinese pork market. Prev. Vet. Med. 215, 105912.

Altizer, S., Ostfeld, R.S., Johnson, P.T.J., Kutz, S., Harvell, C.D., 2013. Climate change and infectious diseases: from evidence to a predictive framework. Science 341 (6145), 514–519.

Andreyeva, T., Long, M.W., Brownell, K.D., 2010. The impact of food prices on consumption: a systematic review of research on the price elasticity of demand for food. Am. J. Public Health 100, 216–222.

Bakhtavoryan, R., Hovhannisyan, V., Devadoss, S., Lopez, J., 2021. An empirical evaluation of egg demand in the United States. J. Agric. Appl. Econ. 53 (2), 280–300.

Beach, R.H., Kuchler, F., Leibtag, E.S., Zhen, C., 2008. The Effects of Avian Influenza News on Consumer Purchasing Behavior: A Case Study of Italian Consumers. USDA, Washington, DC, USA.

Hadachek, J., Ma, M., Sexton, R.J., 2024. Market structure and resilience of food supply chains under extreme events. Am. J. Agric. Econ. 106 (1), 21–44.

Hennessy, D.A., Marsh, T.L., 2021. Economics of animal health and livestock disease. Handb. Agric. Econ. 5, 4233–4330.

Hennessy, D.A., Rault, A., 2023. On systematically insufficient biosecurity actions and policies to manage infectious animal disease. Ecol. Econ. 206, 107740.

Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J., Said, M.Y., Pfeiffer, D.U., 2013. Zoonosis emergence linked to agricultural intensification and environmental change. Proc. Natl. Acad. Sci. 110 (21), 8399–8404.

Jones, K.E., Patel, N.G., Levy, M.A., Storeygard, A., Balk, D., Gittleman, J.L., Daszak, P., 2008. Global trends in emerging infectious diseases. Nature 451 (7181), 990–993.

Karakoc, D.B., Konar, M., Puma, M.J., Varshney, L.R., 2023. Structural chokepoints determine the resilience of agri-food supply chains in the United States. Nature Food. 1–9.

Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., Mitchell, C.E., 2010. Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature 468 (7324), 647–652.

Lee, J., Schulz, L.L., Hoffman, E., Tonsor, G.T., 2023. How can reporting on foreign animal diseases affect meat purchases? The case of African swine fever. Agric. Resour. Econ. Rev. 51, 89–111.

MacDonald, J.M., 2020. Tracking the consolidation of U.S. agriculture. Appl. Econ. Perspect. Policy 42 (3), 361–379.

Malone, T., Lusk, J.L., 2016. Putting the chicken before the egg price: An "Ex Post" analysis of California's battery cage ban. Agric. Resour. Econ. Rev. 41 (3), 518–532.

Malone, T., Schaefer, K.A., Lusk, J.L., 2021. Unscrambling U.S. egg supply chains amid COVID-19. Food Policy 101, 102046.

Marsh, T., Schroeder, T., Mintert, J., 2004. Impacts of meat product recalls on consumer demand in the USA. Appl. Econ. 36 (9), 897–909.

Nerlove, M., 1979. The dynamics of supply: retrospect and prospect. Am. J. Agric. Econ. 61 (5), 874–888.

Okrent, A.M., Alston, J.M., 2011. Demand for food in the United States: a review of literature, evaluation of previous estimates, and presentation of new estimates of demand. In: Giannini Foundation Monograph 48, Giannini Foundation of Agricultural Economics, Berkeley, CA, 2011.

Paini, D.R., Sheppard, A.W., Cook, D.C., De Barro, P.J., Worner, S.P., Thomas, M.B., 2016. Global threat to agriculture from invasive species. Proc. Natl. Acad. Sci. 113 (27), 7575–7579.

Pudenz, C.C., Schulz, L.L., Tonsor, G.T., 2019. Adoption of secure pork supply plan biosecurity by US swine producers. Front. Veter. Sci. 6, 146–160.

Schulz, L.L., Tonsor, G.T., 2015. Assessment of the economic impacts of porcine epidemic diarrhea virus in the United States. J. Anim. Sci. 93 (11), 5111–5118.

Seeger, R.M., Hagerman, A.D., Johnson, K.K., Pendell, D.L., Marsh, T.L., 2021. When poultry take a sick leave: Response costs for the 2014–2015 highly pathogenic avian influenza epidemic in the USA. Food Policy 102, 102068.

Stevens, A.W., Teal, J., 2023. Diversification and resilience of firms in the agri-food supply chain. Am. J. Agric. Econ. 106 (2), 739–778.

Subramaniam, A., Wahdat, A.Z., Lusk, J.L., 2023. Changes in U.S. Food Prices. Center for Food Demand Analysis & Sustainability. Available online at: https://ag.purdue.edu/cfdas/resource-library/changes-in-u-s-food-prices/.

Thompson, J.M., 2018. Effects of regionalized trade restrictions on quantity exported during a highly pathogenic avian influenza event. J. Agric. Appl. Econ. 50 (2), 270–289.

Thompson, J.M., Trejo-Pech, C.J., Pendell, D.L., 2019a. Agribusiness value impacts from highly pathogenic avian influenza. Agric. Fin. Rev. 79 (3), 371–385.

Thompson, J.M., Pendell, D.L., Boyer, T., Patyk, K.A., Malladi, S., Weaver, J.T., 2019b. Economic impacts of business continuity on an outbreak of highly pathogenic avian influenza in Minnesota egg laying operations. J. Agric. Appl. Econ. 51 (2), 235–248.

Tonsor, G.T., 2022. Meat Demand Monitor. Kansas State University, Department of Agricultural Economics, Ag Manager Website. Available at: https://www.agmanager.info/livestock-meat/meat-demand/monthly-meat-demand-monitor-survey-data.

U.S. Department of Agriculture, National Agricultural Statistics Service. Chicken and Eggs. Available at: https://usda.library.cornell.edu/concern/publications/fb494842n?locale=en.

U.S. Department of Agriculture, National Animal Health Monitoring System, 2014. Layers 2013 Part I: Reference of Health and Management Practices on Table-Egg Farms in the United States, 2013. USDA:APHIS:VS.

U.S. Department of Agriculture, Office of the Chief Economist, 2023. World Agricultural Supply and Demand Estimates Report (WASDE). Available at: https://www.usda.gov/oce/commodity/wasde/.

United Egg Producers, 2024. Facts and Stats – Utilization of U.S. Eggs. Available at: https://unitedegg.com/facts-stats/.

USDA-AMS, 2023. Run a Custom Report. USDA AMS Livestock, Poultry, and Grain Market News. Available at: https://marketnews.usda.gov/mnp/py-report-config.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service (USDA-APHIS), 2011. Structure of the U.S. Poultry Industry, 2010. Available at: https://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/poultry10/Poultry10_dr_Structure_1.pdf.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service (USDA-APHIS), 2014. NAHEMS guidelines: surveillance, epidemiology, and tracing. FAD PreP Foreign Animal Disease Preparedness and Response Plan. Available at: https://www.aphis.usda.gov/animal_health/emergency_management/downloads/nahems_guidelines/nahems_sur_epi_trac.pdf.

USDA-APHIS, 2022. WOAH and International Standards. Available at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/nvap/NVAP-Reference-Guide/Animal-Health-Emergency-Management/OIE-and-International-Standards.

USDA-APHIS, 2023. 2022-2023 Confirmations of Highly Pathogenic Avian Influenza in Commercial and Backyard Flocks. Available at: https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-disease-information/avian/avian-influenza/hpai-2022/2022-hpai-commercial-backyard-flocks.

U.S. Department of Agriculture, Economic Research Service (USDA-ERS), 2023a. Wholesale Egg Prices Tumble as Egg Supplies Recover. Available at: https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=106845.

USDA-ERS, 2023b. Poultry Sector at a Glance. Available at: https://www.ers.usda.gov/topics/animal-products/poultry-eggs/sector-at-a-glance/#:~:text=Total%20poultry%20sector%20sales%20in,broilers%20increased%20production%20from%202021.

USDA-ERS, 2023c. Food Availability (Per Capita) Data System. Available at: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.

Von Cramon-Taubadel, S., Goodwin, B.K., 2021. Price transmission in agricultural markets. Ann. Rev. Resour. Econ. 13, 65–84.

Wahdat, A.Z., Lusk, J.L., 2023. The Achilles heel of the US food industries: exposure to labor and upstream industries in the supply chain. Am. J. Agric. Econ. 105 (2), 624–643.

Wang, L.F., Crameri, G., 2014. Emerging zoonotic viral diseases. Rev. Sci. Tech. 33 (2), 569–581.

Wang, Y., Massa, O.I., Stewart, S.L., 2024. Time-varying reaction of U.S. meat demand to animal disease outbreaks. Appl. Econ. Perspect. Policy 1–27.

Xiong, T., Zhang, W., Chen, C.T., 2021. A Fortune from misfortune: Evidence from hog firms' stock price responses to China's African Swine Fever outbreaks. Food Policy 105, 102150.