Production Dynamics and Disruption Responses in the Pork Supply Chain: A Structural Model of Hog and Pig Markets

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ABSTRACT

Analysis of feeder and early weaned pig markets, important segments in pork production, is nearly non-existent. As the industry has integrated, pig markets have become residual markets. They provide price discovery in normal conditions and help the pork supply chain quickly adapt in times of disruption. Using the National Direct Delivered Feeder Pig report, published by the U.S. Department of Agriculture Agricultural Marketing Service, we derive and estimate a structural econometric model relating demand and supply for market hogs, feeder pigs, and early weaned pigs. Results indicate that hog and pig markets are most sensitive to hog processing plant utilization relative to capacity and that this sensitivity has increased compared to prior estimates. Hog and pig production decisions are influenced by market hog prices, wholesale pork demand, feed prices, herd management, and disease prevalence. Estimates from the econometric model predict how disruptions are transmitted through hog and pig markets. A set of counterfactual scenarios quantify the effects of hog processing capacity, wholesale pork demand, and supply response on hog and pig markets. These results have implications for market participants seeking to manage risk and for policymakers designing laws to strengthen the supply chain.

Keywords: pork, hogs, feeder pigs, early weaned pigs, supply chain, wholesale demand, COVID-19

Introduction

In 2020, the popular press used words like “unprecedented,” and “unparalleled” quite often when describing the pork supply chain. Such superlatives seemed appropriate as it was one of the worst disruptions ever to the U.S. pork industry, prompting comparisons to the fall of 1998, and not without merit. Hog slaughter and pork processing bottlenecks in the spring of 2020 quickly devolved into producer-level challenges due to the stark reduction in packing plant operations. Bottlenecks and backlogs in the supply chain are acute in the pork industry. As market-ready hogs back up on the farm, there is no place to keep pigs until spaces emerge at finishing facilities.

Public interest in the pork supply chain was renewed in the aftermath of these disruptions. Executive and legislative actions were taken to address perceived weaknesses as the pork supply chain recovered. While acute disruptions related to COVID-19 ceased, the industry faced a host of new issues related to the new operating environment. By 2023 farrow to finish production costs were 53% higher than in 2020 (Schulz, 2024). Retail pork demand was also lower in 2023, relative to the strong levels the prior three years, putting downward pressure on prices for market hogs and pigs, contributing to one of the worst years financially in recent memory for pork producers (Tonsor, 2024). Animal confinement legislation such as California’s Proposition 12 and Massachusetts’s Question 3 add additional costs and placed further strain on the pork supply chain (Lee et al., 2023; Ufer, 2022). These issues—and their uncertain consequences and future—ensure that the pork industry will remain policy-relevant for the foreseeable future. Predicting the effects of various disruptions is difficult, however, because little is known about the economic framework that connects the various stages of the pork supply chain.

We derive a conceptual framework linking markets for market hogs, feeder pigs, and early weaned pigs that captures salient features of production practices and industry structure. Using publicly available data, we then estimate a structural model to quantify factors affecting supply and demand of both market hogs and pigs. Results speak to the live animal segment's sensitivity to hog processing plant capacity utilization and how disruptions are transmitted across markets. We then employ coefficient estimates from the model to quantify the effects of shocks to processing capacity, wholesale pork demand, and supply shifts in counterfactual scenarios. With our empirical findings, we outline an array of implications that guide decision-making for industry participants and policymakers.

Industry Background

While not particularly esoteric, the steps in bringing a hog to market are necessary to understand the importance of early weaned pig and feeder pig markets. There are four key stages in producing a market hog (Hoar & Angelos, 2015; Pork Checkoff, n.d.; USDA-ERS, 2021). First is gestation, or pregnancy, which takes 115 days. When the sow or gilt gives birth, or farrows, the lactation phase begins, which is typically three weeks in length and concludes when producers wean pigs. Once weaned, pigs enter the nursery phase for the next three to seven weeks. This may be at a dedicated nursery operation or a wean-to-finish operation that encompasses multiple phases. The final phase can be split into two subphases, growing and finishing. The growing phase takes pigs from 35–60 pounds to 120–150 pounds, and the finishing phase takes pigs from 120–150 pounds to their market (live) weight of 250–300 pounds. Growing and finishing takes approximately four months. For pigs in a wean-to-finish operation, producers do not move pigs again; however, in a feeder-to-finish operation they do move pigs from a nursery facility to a dedicated grow-finish facility. In total, it takes six months

from birth to market or ten months including gestation. Under normal operating conditions, the flow of pigs from farm to fork is uninterrupted. However, even seemingly small disruptions can have major impacts on the supply chain.

In 1998, a reduction in slaughter capacity during a wave of packer consolidation resulted in a dramatic fall in hog prices. The cause was a sudden 8.29% drop in hog processing capacity as several U.S. packing plants closed or reduced capacity (Fabiosa & Kaus, 2015). Despite taking measures to mitigate the situation in 1998, many producers went out of business (Barboza, 1998). The structure of the pork industry changed dramatically following 1998. Fewer operations produced more hogs, and each stage of the supply chain became more tightly integrated (Haley, 2024). However, capacity constraints at the packer level remained an issue for the live animal segment of the pork supply chain.

A "positive" structural change was the unprecedented addition of hog processing capacity in the late 2010s. Large plant openings in 2017 and 2019 may have increased capacity by as much as 32,200 head per day (Meyer, 2017; Meyer, 2019). One estimate suggests an additional increase of 2,300 head per day from fall 2019 to fall 2020, despite COVID-19-related pressures (Meyer, 2020b). While the relationship between slaughter capacity and actual slaughter depends on a variety of factors, the 2020 bottleneck could have certainly been worse without the large expansion of physical packing plant capacity that occurred.

As the pork industry adapted to the unprecedented situation presented by COVID-19, a host of challenges around the ability to process market-ready hogs developed. Unlike prior hog processing capacity disruptions related to market conditions, the situation in 2020 was predicated on labor challenges. One key component of understanding this situation is to consider the volume of market-ready hogs not delivered during intended marketing windows due to reduced

pork packing operations. The National Pork Producers Council estimated that at the height of slaughter disruptions "up to 10,069,000 market hogs will need to be euthanized between the weeks ending on April 25 and September 19" (NPPC, 2020). A less pessimistic scenario was euthanizing about five to six million head (Meyer, 2020a; Miller, 2020). It was difficult to project the likelihood, duration, and extent to which the collective hog processing industry could operate at particular levels, which caused a large range in estimates regarding the backlog of market hogs. Other unknowns were the success and prevalence of adjusting pigs' diets, increasing stocking densities, sorting or topping off pens, finding additional facilities to house pigs, and selling into alternative markets to partially mitigate live animal supply chain disruptions (Hayes et al., 2020).

Subsequent to COVID-19 disruptions, the pork industry entered a high-price, high-cost period of production. A key structural change during this period was the closure or reduction of several slaughter facilities. Smithfield Foods announced that it would cease slaughter operations at its Gwaltney, Virginia plant in July 2021 and its Vernon, California plant in June 2022. (Meyer, 2021, 2022). By 2023, a relatively high supply and softening demand placed downward pressure on pork prices (Tonsor, 2024). This filtered upstream into markets for hogs and pigs, driving down prices in those markets as well. Responding to these unfavorable conditions, Smithfield Farms closed 35 sow farms in Missouri (Hess, 2023). Additional closures in 2023 were Hylife's Windom, Minnesota, pork processing plant, and some of Olymel's processing facilities in Canada (Schulz & Crespi, 2024). Then in March 2024, Tyson announced it was closing its Perry, Iowa slaughter plant in June (Meyer, 2024). Processing plant and farm closures do not necessarily reduce hog processing capacity or inventories in the aggregate. Market hogs

can be transported to other facilities for slaughter, and sows can be moved to new or expanded farms elsewhere.

In the wake these recent disruptions, there is increased public interest in the pork sector. Legislative and executive action, notably the Executive Order on Promoting Competition in the American Economy, has targeted a host of issues in the pork sector. A key provision, § 5(i)(iii)(E), directed the Secretary of Agriculture to submit a plan for investments that could bolster competition in agricultural markets (Executive Order No. 14,036, 2021). In response, the United States Department of Agriculture sought to expand hog processing capacity to prevent bottlenecks like those in spring 2020 (The White House, 2022). At the other end of the supply chain, sow farm closures may reduce pig supply and raise prices. Predicting the effects of processing capacity changes, demand fluctuations, herd management, and proposed legislative action and policies requires an end-to-end model of the live animal segment of the pork supply chain. We propose a model that connects production stages along the pork supply chain so that the effects of disruptions and policies can be better understood.

Conceptual Model

The pork supply chain begins with farrowing operations that keep sows for the purpose of farrowing pigs. There are three types of farrowing operations: farrow-to-finish, farrow-to-wean, and farrow-to-feeder. Farrow-to-finish operations keep pigs and feed them until ready for slaughter. Farrow-to-wean operations sell pigs after weaning, typically around 21 days of age and 10–12 pounds. Farrow-to-feeder operations keep pigs after weaning, feed them, and then sell following the nursery stage when they weigh 40–60 pounds. While nursery-only operations that buy weaned pigs and sell at the end of the nursery phase do exist, they are not split out in our model. Since we only consider pig sales by farrow-to-wean and farrow-to-feeder operations,

these are the relevant suppliers of pigs. Finishing operations buy pigs as an input in raising hogs. Wean-to-finish producers buy early weaned pigs from farrow-to-wean operations and feed them for five months before they are ready for slaughter. Feeder-to-finish operations buy feeder pigs from farrow-to-feeder operations and feed them for four months, at which point they are ready for slaughter. When ready for slaughter, hogs are purchased by packers and processed into pork that is then sold into end-user markets.

Price discovery for early weaned and feeder pigs occurs through negotiation (cash) or formulas.[1] Conceivably, then, there are four markets for pigs: cash- and formula-priced early weaned pigs, and cash- and formula-priced feeder pigs. Formula pricing for feeder pigs was common before 2012, but reporting since then is infrequent, so we exclude it from our analysis. Formula pricing for early weaned pigs is common, but formula terms are not well understood. Contracts for early weaned formula pigs may rely on cash prices for pigs or other market prices, such as feed, hog, or pork prices. Since we use aggregate data, we cannot identify heterogeneous contract terms. Hence, we also exclude formula-priced early weaned pigs and focus on cash-priced early weaned and feeder pigs. To the extent that formulas depend on cash prices or an operation participates in both formula and cash markets, the model may be underspecified. Despite this, buyers and sellers predetermine formulas in an earlier negotiating stage, so separating cash and formula markets at the time of sale is still reasonable.

We model the live-animal segment with one system of nine equations that relate inverse demand, supply, and market clearing conditions for market hogs, feeder pigs, and early weaned pigs. McKendree et al. (2019) similarly construct a system of supply and inverse demand

[1] Examples of methods used to establish formulas for pricing feeder pigs include the spot feeder pig market, adjusted for weight and performance; a percentage of a lean hog futures contract; cost of production; cost of production plus a premium for increased performance; and profit sharing between different stages of production (DiPietre et al., 2006; Seddon, n.d.).

equations for feeder and fed cattle. Our model is analogous with salient features of the pork supply chain that builds upon the work of Reid & Reed (1982) and Parcell et al. (2004). The system is specified as:

$$P_t^{M,D} = \phi\left(Q_t^{M,D}, WDI_t, Utilization_t, t, Seasonality\right) \quad (1)$$

$$Q_t^{M,S} = \phi\left(\begin{matrix} E_{t-17}[P_t^{M,S}], E_{t-22}[P_t^{M,S}], P_{t-17}^{CN,S}, P_{t-22}^{CEW,S}, P_{t-17}^{F}, P_{t-22}^{F}, Q_{t-17}^{M,S}, Q_{t-22}^{M,S}, PackerShare_t, \\ t, Seasonality \end{matrix}\right) \quad (2)$$

$$P_t^{M,D} = P_t^{M,S} = P_t^{M};\ Q_t^{M,D} = Q_t^{M,S} = Q_t^{M} \quad (3)$$

$$P_t^{CN,D} = \phi\left(Q_t^{CN,D}, E_t\left[P_{t+17}^{M,D}\right], P_t^{F}, SmallLotShare_t, t, Seasonality\right) \quad (4)$$

$$Q_t^{CN,S} = \phi\left(\begin{matrix} P_t^{CN,S}, E_{t-45}\left[P_t^{CN,S}\right], P_{t-25}^{SOW,S}, Q_{t-28}^{CN,S}, Disease_t, ContractorShare_t, P_{t-5}^{CEW}, \\ t, Seasonality \end{matrix}\right) \quad (5)$$

$$P_t^{CN,D} = P_t^{CN,S} = P_t^{CN};\ Q_t^{CN,D} = Q_t^{CN,S} = Q_t^{CN} \quad (6)$$

$$P_t^{CEW,D} = \phi\left(Q_t^{CEW,D}, E_t\left[P_{t+22}^{M,D}\right], P_t^{F}, SmallLotShare_t, t, Seasonality\right) \quad (7)$$

$$Q_t^{CEW,S} = \phi\left(\begin{matrix} E_{t-20}\left[P_t^{CEW,S}\right], P_{t-20}^{F}, E_{t-45}\left[P_t^{CEW,S}\right], P_{t-20}^{SOW,S}, Q_{t-23}^{CEW,S}, Disease_t, \\ ContractorShare_t, t, Seasonality \end{matrix}\right) \quad (8)$$

$$P_t^{CEW,D} = P_t^{CEW,S} = P_t^{CEW};\ Q_t^{CEW,D} = Q_t^{CEW,S} = Q_t^{CEW} \quad (9)$$

Equation (1), the inverse demand for market hogs, models the price of a market hog as a function of the quantity demanded by processors ($Q_t^{M,D}$), demand for wholesale pork (WDI_t), hog processing plant utilization ($Utilization$), and technological change (t) and seasonal effects ($Seasonality$). Demand for wholesale pork is derived from consumers' demand for pork but omits price variation that is specific to retailing, foodservice, or export. Hog processing plant utilization is necessary to evaluate how the market responds when plants run at varying levels of capacity. When a plant is running near full capacity, its marginal cost of processing an additional hog will be high. In the inverse demand equation, technological change measures the trend of prices over time and seasonal effects capture variation in prices related to the time of year.

Equation (2), the supply of market hogs, models the quantity of market hogs supplied as a function of past decisions by feeder-to-finish and wean-to-finish operations ($E_{t-17}[P_t^{M,S}], E_{t-22}[P_t^{M,S}], P_{t-17}^{CN,S}, P_{t-22}^{CEW,S}, P_{t-17}^{F}, P_{t-22}^{F}, Q_{t-17}^{M,S}, Q_{t-22}^{M,S}$), the contemporaneous share of slaughtered hogs owned or sold by a packer ($PackerShare_t$), technological change (t), and seasonal effects ($Seasonality$). The price a feeder-to-finish or wean-to-finish operation expected to receive for a market hog ($E_{t-17}[P_t^{M,S}], E_{t-22}[P_t^{M,S}]$) is the expected price of a market hog at the time that operation purchased a pig to raise. These terms are the expected prices of a market hog from 17 and 22 weeks prior, the time required to raise a feeder or early weaned pig for market. The price a feeder-to-finish (wean-to-finish) operation paid for a feeder (early weaned) pig is $P_{t-17}^{CN,S}$ ($P_{t-22}^{CEW,S}$), which is simply the cash price of a feeder (early weaned) pig from 17 (22) weeks prior. Similarly, feed prices ($P_{t-17}^{F}, P_{t-22}^{F}$) were paid 17 or 22 weeks prior when the pigs were purchased. The quantity of market hogs from 17 and 22 weeks prior ($Q_{t-17}^{M,S}, Q_{t-22}^{M,S}$) capture the flow of animals from finishing operations to processors at the time a finishing operation

purchased its current group of pigs.[2] Packers' share of owned or sold hogs is included to account for flows of pigs in and out of market channels. In the supply equation, technological change measures the trend of quantity supplied over time, and seasonal effects capture variation in quantity supplied related to the time of year. Equation (3) is the market clearing condition that relates inverse demand for market hogs (1) with the supply of market hogs (2).

Equation (4), the inverse demand for cash-priced feeder pigs, models the cash price for feeder pigs as a function of the quantity demanded by feeder-to-finish producers $\left(Q_t^{CN,D}\right)$, the market hog price those producers expect to receive when pigs are ready for slaughter $\left(E_t\left[P_{t+17}^{M,D}\right]\right)$, current feed prices (P_t^F), the share of feeder pigs marketed in lots of fewer than 1,200 pigs $(SmallLotShare_t)$, technological change (t), and seasonal effects $(Seasonality)$. The time period on expected prices for market hogs reflects the 17 weeks from weaning until slaughter. Feed prices capture the variable input costs of raising a pig for market. Producers evaluate the price they expect to receive for a pig and the cost of raising that pig when choosing the quantity to purchase. When pigs are marketed in small lots, a buyer may have to purchase multiple lots to fill a barn. The small lot share variable proxies for increases to transaction costs due to farrow-to-feeder operations marketing pigs in lots smaller than a conventional feeder-to-finish barn. Like the inverse demand for market hogs, technological change measures the trend of prices over time and seasonal effects capture variation in prices related to the time of year.

Equation (5), the supply of cash-priced feeder pigs, models the quantity of cash-priced feeder pigs as a function of current cash price for feeder pigs $\left(P_t^{CN,S}\right)$, past decisions made by farrow-to-feeder operations that affect current inventories of early weaned pigs

[2] To make this concrete, consider a feeder-to-finish operation with a 2,400-head barn. Every 17 weeks, this operation sells 2,400 market hogs and replaces them with 2,400 feeder pigs. The 17-week lagged quantity term in equation (2) aggregates this to control for the flow of animals through finishing operations.

$\left(E_{t-45}\left[P_t^{CN,S}\right], P_{t-25}^{SOW,S}, Q_{t-28}^{CN,S}, P_{t-5}^{CEW}\right)$, current disease prevalence $(Disease_t)$, the share of hogs raised under production contracts $(ContractorShare_t)$, technological change (t), and seasonal effects $(Seasonality)$. The current price for cash-priced early weaned pigs is the opportunity cost of selling today versus retaining the animal. The opportunity cost of retaining a gilt for farrowing $\left(E_{t-45}\left[P_t^{CEW,S}\right]\right)$ is the expected price of a cash-priced feeder pig when making the decision whether to retain that gilt. This period is 45 weeks, which includes 20 weeks from the retention decision until the animal is ready to breed, 17 weeks for gestation, 3 weeks from farrowing to weaning, and then 5 weeks in a nursery. The opportunity cost of retaining a sow for farrowing $\left(P_{t-25}^{SOW,S}\right)$ is the price of a sow 25 weeks in the past, which includes 17 weeks for gestation, 3 weeks from farrowing to weaning, and 5 weeks in a nursery. The term $(Q_{t-28}^{CN,S})$ accounts for the flow of feeder pigs from farrow-to-feeder operations to feeder-to-finish at the time a farrow-to-feeder operation bred its current group of pigs. This is accounted for in the lag structure: 3 weeks between weaning a litter and the beginning of the next gestation cycle, 17 weeks for gestation, 3 weeks from farrowing to weaning, and 5 weeks in a nursery. In principle, a farrow-to-feeder operation can sell a pig after weaning. The opportunity cost of retaining an early weaned pig for the nursery stage (P_{t-5}^{CEW}) is the price a farrow-to-feeder operation could have received for a pig 5 weeks prior when that pig was weaned. This captures the inventory effect of past prices for early weaned pigs on the current supply of feeder pigs. Intuitively, this could be a farrow-to-feeder operation choosing to take a first cut of pigs that are sold on a 10–12-pound basis and then a second cut that are sold on a 40-pound basis. Finally, current disease prevalence directly affects inventories of feeder pigs, which are susceptible to viral infections such as porcine epidemic diarrhea virus (PEDV) and porcine reproductive and respiratory syndrome (PRRS) that have high mortality rates (Pospischil et al., 2002; Leedom Larson, 2016).

Similar to the supply of market hogs, we need to account for flows in and out of marketing channels. We account for this with the share of hogs raised under a production contract, which is a broader measure than the packer share of slaughtered hogs. Like the supply of market hogs, technological change measures the trend of quantity supplied over time, and seasonal effects capture variation in quantity supplied related to the time of year. Equation (6) is the market clearing condition that relates the inverse demand (4) and supply (5) equations for cash-priced feeder pigs.

Equation (7), the inverse demand for cash-priced early weaned pigs, is similar to equation (4), the inverse demand for cash-priced feeder pigs. Its terms are specified for early weaned pigs. The period for expected prices, 22 weeks, is increased by the 5 weeks an early weaned pig will spend in a nursery.

Equation (8), the supply of cash-priced early weaned pigs, is similar to equation (5), the supply of cash-priced feeder pigs. Periods are shortened by 5 weeks since farrow-to-wean operations do not include a nursery stage.[3] The supply of cash-priced early weaned pigs, equation (8), specifies the quantity of cash-priced early weaned pigs supplied as a function of expected pig prices ($E_{t-20}\left[P_t^{CEW,S}\right]$) and feed prices ($P_{t-20}^{F}$) at the beginning of gestation. In contrast, the supply of cash-priced feeder pigs, equation (5), specifies the quantity of cash-priced feeder pigs as a function of contemporaneous cash prices for feeder pigs ($P_t^{CN,S}$). This is because pigs rapidly outgrow the farrowing pen after weaning and the transition to feed, more than doubling in weight in the three weeks after weaning (Schnickel et al., 2004). In the nursery phase, however, pigs can be commingled at the risk of exposing younger pigs to pathogens from

[3] The opportunity cost of retaining a gilt ($E_{t-45}\left[P_t^{CEW,S}\right]$) has the same period for feeder and early weaned pigs. For early weaned pigs, this period is 25 weeks from the retention decision until the animal is ready to breed, 17 weeks for gestation, and 3 weeks from farrowing to weaning.

older pigs (Fangman & Tubbs, 1997). Equation (9) is the market clearing condition for cash-priced early weaned pigs.

Data

We derive data used in this analysis from publicly available sources. Unless otherwise specified, all data are at a weekly level and span January 2013 to December 2023. Prices are deflated by the Prices Paid Index for Commodities and Services, Interest, Taxes, and Wage Rates (PPITW) published by the USDA's National Agricultural Statistics Service (USDA-NASS), and all monthly or quarterly variables are imputed to a weekly level using linear interpolation.

Pig producers voluntarily report feeder pig sales to USDA's Agricultural Marketing Service (USDA-AMS). USDA-AMS groups feeder pigs into 10–12-pound pigs (early weaned) and 40-pound (feeder) pigs. For each category, USDA-AMS further classifies transactions as either cash or formula. Quoted prices are on a per head basis delivered to the buyer's farm and include freight and fees. USDA-AMS adjusts prices by a slide to conform to the 10–12- and 40-pound reporting categories.[4] Data are from the USDA-AMS National Direct Feeder Pig report. The Livestock Marketing Information Center (LMIC) compiles the weekly data into a spreadsheet. These data provide feeder pig prices and quantities for the two categories ($P_t^{CEW}, Q_t^{CEW}, P_t^{CN}, Q_t^{CN}$). For the opportunity costs of retaining a gilt ($E_{t-45}[P_t^{CEW}], E_{t-45}[P_t^{CN}]$), we adopt a naïve expectations approach, similar to McKendree et al. (2019), and simply use a 45-week lag of the relevant feeder pig price ($P_{t-45}^{CEW}, P_{t-45}^{CN}$). This dataset also contains the number of pigs sold by lot size: <600, 600-1200, and >1200 head. We construct the $SmallLotShare_t$ variables as the number of cash-priced early weaned (feeder) pigs sold in

[4] For additional details on feeder pig reporting, see https://www.ams.usda.gov/sites/default/files/media/LPGMNReporterHandbook.pdf.

lots of <600 or 600-1200 divided by the total number of cash-priced early weaned (feeder) pigs sold in a given week.

We assume that USDA-reported data on feeder pig sales is representative of all feeder pig transactions. Producers report data to USDA voluntarily, which covers roughly 5% of hogs raised for slaughter. Since reporting is voluntary, there are feeder pig sales not accounted for in USDA data. Pigs within an integrated system are transferred inter-farm but not marketed. This is a growing share as more pigs are raised under production contracts. USDA does not grade feeder pigs; thus, we cannot control for variation in health and other characteristics. USDA takes steps to ensure data quality and representativeness, and we are unaware of any evidence that reported and non-reported prices or attributes are systemically different (USDA-AMS, 2021).

For market hog prices (P_t^M) and quantities (Q_t^M), we use the CME Lean Hog Index and its corresponding volume. This is a representative price for hogs that are marketed in the cash market or use formulas that establish prices in reference to cash hog prices and/or pork cutout values.[5] Data are compiled by LMIC and then aggregated to a weekly level by taking a volume-weighted average of the daily data. Under the assumption of naïve expectations, these prices are also used for the expected price of a market hog in the market hog supply and feeder pig demand equations. That is, we use P_{t-22}^M for $E_{t-22}\left[P_t^{M,S}\right]$ in equation (2) and P_t^M for $E_t\left[P_{t+22}^{M,D}\right]$ in equation (4), and P_{t-17}^M for $E_{t-17}\left[P_t^{M,S}\right]$ in equation (8) and P_t^M for $E_t\left[P_{t+17}^{M,D}\right]$ in equation (10).

We calculate a wholesale demand index (WDI_t) using the pork cutout value and its associated volume from the USDA-AMS National Daily Pork FOB Plant - Negotiated Sales - Afternoon (LM_PK602) report. Data are compiled and aggregated to a weekly level by LMIC.

[5] Details on how the Lean Hog Index is calculated are available in the CME Rulebook: https://www.cmegroup.com/content/dam/cmegroup/rulebook/CME/II/150/152/152.pdf.

This data was incorporated into Livestock Mandatory Reporting in 2013 but reported voluntarily prior to that. The wholesale demand index is calculated similarly to the retail demand index in McKendree et al. (2019) and for the own-price elasticity we use -0.471 from Lusk et al. (2001).

Corn and soybean meal prices are the average prices for the next expiring CME futures contract for all days within a week, data which LMIC compiles. We use these data to construct feed prices by assuming a constant feed ratio of one bushel of corn per nine pounds of soybean meal (Christensen & Schulz, 2022). Our feed price variable (P_t^F) is then the cost per bushel of corn plus nine times the cost per pound of soybean meal.

We derive sow prices from USDA-AMS Daily Direct Prior Day Sow and Boar Report. This report provides daily head counts and weighted average prices in dollars per hundredweight for purchased sows, grouped into weight ranges. We use the price series for sows purchased on a live basis via negotiation. LMIC compiles these data and aggregates daily prices to a weekly level by taking the head-weighted average. We then take the head-weighted average of sow prices for three weight ranges—300 to 449 pounds, 450 to 499 pounds, and 500 pounds and above—to construct our sow price variable (P_t^{SOW}).

To proxy for disease prevalence, we use pre-wean mortality (PWM_t) data from PigCHAMP (n.d.). This data is available at a quarterly level and represents the percentage of pigs that are born alive but die before weaning. PigCHAMP collects these data every quarter from thousands of sows farrowing across hundreds of farms that implement its data collection and management software.

Contractor shares are taken directly from quarterly USDA-NASS Hogs and Pigs reports and imputed to a weekly level. These shares are the total number of hogs raised by contractees

but owned by operations with over 5,000 head divided by the total United States hog and pig inventory.

Hog processing plant utilization and capacity, and packer hog share are derived from slaughter data in the USDA-AMS National Daily Direct Hog Prior Day Report - Slaughtered Swine (LM_HG201), also compiled and aggregated to a weekly level by LMIC. We construct a utilization-to-capacity ratio ($Utilization_t$) by dividing the current week's slaughter by the highest slaughter for the current week from the prior three years (Tonsor & Schulz, 2020). The packer hog share variable is simply the number of slaughtered hogs owned or sold by a packer—i.e., not sold by a producer—divided by total slaughter.

Lastly, consumer sentiment data is imputed from the monthly Index of Consumer Sentiment published by the University of Michigan's Survey of Consumers. This index (CSS_t), linearly interpolated to a weekly level, captures consumers' assessment of current and expected economic conditions in the United States. We use this as an instrument for the wholesale demand index in the empirical model.

Empirical Model

We assume naïve expectations for the opportunity costs of retaining a gilt and value of a market hog at slaughter, consistent with McKendree et al. (2019). For estimation, however, we implement a two-step GMM procedure. In contrast to the three-stage least squares approach, GMM's instrument requirements, especially system-wide exogeneity, are less restrictive (Wooldridge, 2002, Chapter 8). We use the IVSystemGMM module of the *linearmodels* package in Python 3.8 to conduct estimation.[6] In all cases, we use heteroskedasticity-robust standard errors. We specify all equations in log-log form, excluding share variables that are already a

[6] A comparison of system GMM and three-stage least squares procedures is provided in the *linearmodels* 5.4 documentation: https://bashtage.github.io/linearmodels/system/examples/three-stage-ls.html.

percentage; thus, we can interpret coefficients as elasticities or flexibilities. Finally, we include a linear time variable (t) and vector of monthly dummies with January excluded $(\boldsymbol{D_m})$ to account for technological change and seasonality, respectively. The dummy vector also includes a year dummy for 2020 to adjust for any reporting behavior changes in voluntarily reported feeder pig data and other issues related to COVID-19 not captured in the model.

We specify the system of equations as:

$$\ln P_t^M = \alpha_0^M + \alpha_1^M \ln Q_t^M + \alpha_2^M \ln WDI_t + \alpha_3^M \ln Utilization + \alpha_4^M t + \boldsymbol{\alpha_m^M D_m} + \varepsilon_t^{M,D} \quad (40)$$

$$\begin{aligned} \ln Q_t^M = {} & \beta_0^M + \beta_1^M \ln P_{t-17}^M + \beta_2^M \ln P_{t-22}^M + \beta_3^M \ln P_{t-17}^{CN} + \beta_4^M \ln P_{t-22}^{CEW} + \beta_5^M \ln P_{t-17}^F \\ & + \beta_6^M \ln P_{t-22}^F + \beta_7^M \ln Q_{t-17}^M + \beta_8^M \ln Q_{t-22}^M + \beta_9^M PackerShare_t + \beta_{10}^M t \\ & + \boldsymbol{\beta_m^M D_m} + \varepsilon_t^{M,S} \end{aligned} \quad (51)$$

$$\begin{aligned} \ln P_t^{CN} = {} & \alpha_0^{CN} + \alpha_1^{CN} \ln Q_t^{CN} + \alpha_2^{CN} \ln P_t^M + \alpha_3^{CN} \ln P_t^F + \alpha_4^{CN} SmallLotShare_t^{CN} + \alpha_5^{CN} t + \boldsymbol{\alpha_m^{CN} D_m} \\ & + \varepsilon_t^{CN,D} \end{aligned} \quad (12)$$

$$\begin{aligned} \ln Q_t^{CN} = {} & \beta_0^{CN} + \beta_1^{CN} \ln P_t^{CN} + \beta_2^{CN} \ln P_{t-45}^{CN} + \beta_3^{CN} \ln P_{t-25}^{SOW} + \beta_4^{CN} \ln Q_{t-28}^{CN} + \beta_5^{CN} PWM_t \\ & + \beta_6^{CN} ContractorShare_t + \beta_7^{CN} \ln P_{t-5}^{CEW} + \beta_8^{CN} t + \boldsymbol{\beta_m^{CN} D_m} + \varepsilon_t^{CN,S} \end{aligned} \quad (13)$$

$$\begin{aligned} \ln P_t^{CEW} = {} & \alpha_0^{CEW} + \alpha_1^{CEW} \ln Q_t^{CEW} + \alpha_2^{CEW} \ln P_t^M + \alpha_3^{CEW} \ln P_t^F + \alpha_4^{CEW} SmallLotShare_t^{CEW} \\ & + \alpha_5^{CEW} t + \boldsymbol{\alpha_m^{CEW} D_m} + \varepsilon_t^{CEW,D} \end{aligned} \quad (14)$$

$$\begin{aligned} \ln Q_t^{CEW} = {} & \beta_0^{CEW} + \beta_1^{CEW} \ln P_{t-20}^{CEW} + \beta_2^{CEW} \ln P_{t-20}^F + \beta_3^{CEW} \ln P_{t-45}^{CEW} + \beta_4^{CEW} \ln P_{t-20}^{SOW} \\ & + \beta_5^{CEW} \ln Q_{t-23}^{CEW} + \beta_6^{CEW} PWM_t + \beta_7^{CEW} ContractorShare_t + \beta_8^{CEW} t \\ & + \boldsymbol{\beta_m^{CEW} D_m} + \varepsilon_t^{CEW,S} \end{aligned} \quad (15)$$

Equation (10) is the inverse demand for market hogs. It is analogous to equation (1). Equation (11) is the supply of market hogs. It is analogous to equation (2). Equation (12) is the inverse

demand for cash-priced feeder pigs, and equation (13) is the supply of cash-priced feeder pigs; these correspond to equations (4) and (5). Equations (14) and (15) are the inverse demand for and supply of cash-priced early weaned pigs. They are analogous to equations (7) and (8). We estimate equations (10)–(15) jointly.

In equation (10), the endogenous variables are the quantity of market hogs ($\ln Q_t^M$), wholesale demand index ($\ln WDI_t$), and utilization ($\ln Utilization_t$). In equation (11), all variables are exogenous by construction. We use all unshared independent variables as excluded instruments, so the system is overidentified. For equation (10), the excluded instruments are $\ln P_{t-17}^M$, $\ln P_{t-22}^M$, $\ln P_{t-17}^{CN}$, $\ln P_{t-22}^{CEW}$, $\ln P_{t-17}^F$, $\ln P_{t-22}^F$, $\ln Q_{t-17}^M$, $\ln Q_{t-22}^M$, and $PackerShare_t$. We include consumer sentiment CSS_t as an additional instrument for the wholesale demand index to resolve issues of changing consumer preferences on the demand for pork.

Equation (12) is the inverse demand for cash-priced feeder pigs, and equation (13) is the supply of cash-priced feeder pigs. In equation (12), the endogenous variables are the quantity of cash-priced feeder pigs ($\ln Q_t^{CN}$) and the price of market hogs ($\ln P_t^M$), and the endogenous variable for equation (13) is the cash price of feeder pigs ($\ln P_t^{CN}$). As before, we use exogenous independent variables not common to both equations as excluded instruments, and this system is overidentified. For equation (12), the excluded instruments are $\ln P_{t-45}^{CN}$, $\ln P_{t-25}^{SOW}$, $\ln Q_{t-28}^{CN}$, PWM_t, $ContractorShare_t$, and $\ln P_{t-5}^{CEW}$. For equation (13), the excluded instruments are $\ln P_t^F$ and $SmallLotShare_t^{CN}$.

In equation (14), the endogenous variables are the quantity of cash-priced early weaned pigs ($\ln Q_t^{CEW}$) and the price of a market hog ($\ln P_t^M$). In equation (15), all variables are exogenous by construction. We again use all unshared independent variables as excluded

instruments, so the system is overidentified. For equation (14), excluded instruments are $\ln P_{t-20}^{CEW}$, $\ln P_{t-20}^{F}$, $\ln P_{t-45}^{CEW}$, $\ln P_{t-20}^{SOW}$, $\ln Q_{t-23}^{CEW}$, PWM_t, and $ContractorShare_t$.

Results

Table 1 presents inverse demand and supply estimates for market hog equations (10) and (11). Seasonal variables show that market hog prices are highest in the summer when quantities are lowest. The own-quantity flexibility of demand for market hogs is -0.258, which implies an own-price elasticity of $\frac{1}{-0.258} = -3.876$.[7] That is, for a 1% increase in the market hog price, we would expect a corresponding decrease of 3.876% in the quantity. This flexibility is in line with Parcell et al. (2004), who find an own-quantity flexibility of -0.331 from March 1981 to December 2000, but smaller than Wohlgenant (1989), who finds an own-quantity flexibility of -2.070 from 1956 to 1983. A 1% increase in demand for wholesale pork corresponds to a 0.656% increase in the price of a market hog.[8] Market hog prices are most responsive to hog processing plant capacity utilization. When plant utilization relative to capacity increases by 1%, market hog prices fall 1.914%. This is similar to Tonsor & Schulz (2020) who found a 1.82% decrease in market hog prices, but much larger than Parcell et al. (2004) who report a 0.307% decrease. For the supply of market hogs, the contemporaneous quantity of market hogs is positively related to the prices that feeder-to-finish and wean-to-finish producers expected to receive when buying early weaned pigs 17 and 22 weeks prior and negatively related to the price paid for feeder pigs.

Table 2 contains inverse demand, equation (12), and supply, equation (13), estimates for cash-priced feeder pigs. Seasonal variables indicate that prices are lowest in the summer. The own-quantity flexibility of demand, -0.426, corresponds to an own-price elasticity of -2.347.

[7] This coefficient estimate is marginally significant with a p-value of 0.106.
[8] We are unaware of any existing estimates for the flexibility of hog prices with respect to wholesale pork demand or the elasticity of wholesale pork demand with respect to hog prices.

This is larger than the short-run elasticity estimate of -0.28 from Reid & Reed (1982). They report a long-run elasticity of -1.65, which is closer to our estimate. The elasticity with respect to the expected price of a market hog indicates that a 1% increase in the expected price of a market hogs corresponds to a 1.875% increase in the cash price of feeder pigs. Finally, cash prices for feeder pigs are sensitive to transaction costs. For a 1% increase in the share of cash-priced feeder pigs sold in <1200 head lots, the price falls by 0.594%. All else equal, if a producer must purchase multiple lots of pigs, then transaction costs will be higher. In turn, pigs marketed in small lots are worth less to buyers. The own-price elasticity of supply indicates that a 1% increase in price corresponds to an 8.942% increase in the quantity supplied. As to why this is so elastic, it may be the case that nursery facilities are more accommodating of a variety of pig sizes. In practical terms, feeder pigs are commonly sold between 35 and 60 pounds, and farrow-to-feeder operations are likely able to retain animals over a longer time window than farrow-to-wean operations. Reid & Reed report a short-run elasticity of 0.03 and a long-run elasticity of 0.27, both of which are smaller than our estimate. When cash prices for early weaned pigs were 1% higher 5 weeks prior—when today's feeder pigs were weaned—the current quantity of cash-priced feeder pigs is 5.188% lower. This suggests that farrow-to-feeder operations may take a first cut or opportunistically sell weaned pigs when prices are high.

Table 3 contains inverse demand and supply coefficient estimates for cash-priced early weaned pigs, equations (14) and (15). Prices are lowest in the summer. The own-quantity flexibility of demand is -1.573, which implies an own-price elasticity of -0.636. This is inelastic compared to the own-quantity flexibility of demand for feeder pigs and closer to Reid & Reed's (1982) estimate of -0.28. The elasticity with respect to market hog prices indicates that a 1% increase in market hog prices corresponds to a 1.196% increase in cash prices for early weaned

pigs. Cash prices for feeder pigs, in contrast, increase 1.875% for a 1% increase in expected market hog prices, so cash prices for early weaned pigs are less sensitive to expected market hog prices. Expected market hog prices may be noisier or less reliable for buyers of early weaned pigs since the time to market is 5 weeks longer than for buyers of feeder pigs. Our proxy for transaction costs, the share of cash-price early weaned pigs sold in lots of <1200 head, indicates that when share sold in small lots increases 1%, the cash price for early weaned pigs decreases 2.809%. For feeder pigs, a 1% increase in the share sold in small lots corresponds to a 0.594% decrease in price, so early weaned pig prices are more sensitive to small lots. This may reflect a stronger preference for early weaned pigs from a single source to reduce transaction costs and mitigate biosecurity hazards (Seaman & Fangman, 2023).

For the supply of cash-priced early weaned pigs, the contemporaneous quantity is unrelated to the expected price for an early weaned pig at the beginning of gestation 20 weeks prior, indicated by a lack of statistical significance, but decreases with feed prices at that time. This suggests that breeding continues regardless of expected prices, at least in the short term. Unlike feeder pigs, pre-weaning mortality has a negative effect on the quantity of early weaned pigs. Pre-weaning mortality is a better measure of disease prevalence for early weaned pigs than feeder pigs.

A perk of the system approach is it allows us to evaluate how hog processing plant utilization changes are transmitted to feeder pig markets via prices. For a 1% increase in plant utilization, the corresponding changes in the cash price for feeder and early weaned pigs are:

$$\frac{\partial \ln P_t^{CN}}{\partial \ln P_t^M} \times \frac{\partial \ln P_t^M}{\partial Utilization_t} \text{ and } \frac{\partial \ln P_t^{CEW}}{\partial \ln P_t^M} \times \frac{\partial \ln P_t^M}{\partial Utilization_t}.$$

By construction, these terms are coefficients from the system regression. For feeder pigs, this is $1.875 \times -1.914 = -3.589\%$. For early weaned pigs, this is $1.196 \times -1.914 = -2.289\%$.

Market hog prices decrease 1.914% for a 1% increase in utilization. Thus, feeder pig prices are more sensitive than early weaned pig prices to changes in utilization. This may be a time-to-market difference where feeder pigs are simply 5 weeks closer to market and thus conditions are more certain. The own-quantity flexibilities—% change in price for a 1% increase in quantity—for market hogs, feeder pigs, and early weaned pigs are all smaller than the change in price for a 1% increase in utilization. Hence, all animal prices are more sensitive to utilization than their own quantity.

Since the supply of feeder pigs is modeled with a contemporaneous price, we can evaluate the effect of utilization on the quantity in equilibrium. For a 1% increase in hog processing plant utilization, the corresponding change in the quantity of feeder pigs is:

$$\frac{\partial \ln Q_t^{CN}}{\partial \ln P_t^{CN}} \times \frac{\partial \ln P_t^{CN}}{\partial \ln P_t^{M}} \times \frac{\partial \ln P_t^{M}}{\partial Utilization_t}.$$

Again, we calculate this change using coefficients: $8.942 \times 1.875 \times -1.914 = -32.091\%$. The supply of cash-priced feeder pigs is highly sensitive to changes in utilization. If farrow-to-feeder operations can retain animals for a few weeks or take measures to mitigate overcrowding until plant bottlenecks are resolved, then they are an important source of flexibility in the pork supply chain.

Simulations

Two key periods of disruption that motivate this paper are 2020 and 2023. While the drivers of events during these years are distinct, the common outcome was lower price levels for hogs and pigs. We use the model's results to find the effects of three counterfactual scenarios:

1. What if hog processing plant capacity did not expand and remained at 2016 levels during the second and third quarter of 2020?

2. What if wholesale pork demand in 2023 had stayed at 2022 levels?[9]
3. How much would the supply of hogs and pigs have needed to be reduced in order for producers to break even in 2023?

Because the system of equations relies on lags of prices and quantities, model outputs become model inputs in the future. Hence, a simulation procedure is necessary.

For scenarios 1 and 2, the simulation is similar to McKendree et al. (2019). Baseline values for each scenario are found by predicting prices and quantities for market hogs, feeder pigs, and early weaned pigs using observed values for other variables at the start of the period. These predictions are stored, and the next week is predicted. This continues, and predicted prices and quantities are eventually picked up as lagged prices and quantities in the model. The steps for simulating the 2020 capacity scenario are the same as the 2020 baseline scenario but incorporate a shock to hog processing capacity. This shock comes from substituting the observed utilization for utilization calculated at 2016 capacity levels, i.e., as if capacity were not expanded from 2016 to 2020. The 2023 demand scenario is also simulated like the 2023 baseline but substitutes observed levels of wholesale pork demand from 2023 for levels from 2022.

For scenario 3, reducing hog and pig supply in 2023, the baseline is found as before, but the procedure for simulating shocks differs. This scenario considers the effect of supply on prices, taking demand as given. As such, we fix prices at particular levels where hog and pig producers would break even and then solve for the quantity that satisfies this relationship. Based on Iowa State University's Estimated Livestock Returns - Swine (Schulz, 2024), in 2023 the breakeven prices are assumed to be $95/cwt for finishing operations, $75/head for farrow-to-

[9] Wholesale pork demand levels from 2022 were chosen for comparison because it is the year prior to 2023. Additionally, any COVID-related shocks to wholesale pork demand and consumption patterns should have mostly alleviated by 2022.

feeder operations, and $45/head for farrow-to-wean operations.[10] For market hogs, the resulting calculation is derived from equation (10) as

$$\ln Q_t^M = \frac{1}{\alpha_1^M} \times [\ln(95) - \alpha_0^M - \alpha_1^M - \alpha_2^M \ln WDI_t - \alpha_3^M \ln Utilization - \alpha_4^M t - \boldsymbol{\alpha_m^M D_m}].$$

Similar expressions for the quantity of feeder pigs and early weaned pigs are derived from equations (12) and (14).[11] Like shocks for other scenarios, predicted quantities are stored and used in subsequent predictions. Unlike other scenarios, however, prices remain fixed at the breakeven level.

Results for each counterfactual scenario are shown in table 4. In the first scenario, had processing capacity in the second and third quarter of 2020 been at 2016 levels, market conditions would have been far worse for producers. In the short term, feeder pig supply is responsive to market conditions, but early weaned pig and market hog supplies are fixed. In turn, shocks are transmitted through both prices and quantities for feeder pigs but primarily prices for early weaned pigs and market hogs. Price declines in this scenario are relatively larger for market hogs (19%) and early weaned pigs (23%) than feeder pigs (16%), but revenue decreases sharply in the feeder pig market due to fewer pigs being purchased.

The second scenario quantifies the effects of falling wholesale pork demand in 2023. If wholesale pork demand had stayed at 2022 levels in 2023, prices would have been higher for market hogs (7%), feeder pigs (6%), and early weaned pigs (8%). As in the first scenario, only

[10] These figures are intended to be "in the ballpark" based on total costs from the Estimated Livestock Returns - Swine data (Schulz, 2024). Finishing operations in the model include feeder-to-finish and wean-to-finish. For simplicity, we average the breakeven prices for these operations. The breakeven price for farrow-to-feeder operations ($75/head) is the farrow-to-wean cost ($45/head) plus the cost for wean-to-feeder, less the purchase price for a weaned pig ($30/head).

[11] The supply of feeder pigs is modeled endogenously as a function of the contemporaneous price of feeder pigs. In turn, there are two solutions for the quantity of feeder pigs. However, since demand is fixed at a given price level, we are implicitly ignoring the supply response to the breakeven price and considering only a movement of the supply curve to meet this criteria. That is, we are concerned only with the quantity demanded in this scenario.

feeder pigs would have had a non-negligible supply response, increasing the number of feeder pigs purchased by 23%.

The third scenario finds the quantity of market hogs, feeder pigs, and early weaned pigs at which the price paid for each would be equal to the cost of production. It mirrors the second scenario in the sense that it finds the supply shock necessary to achieve certain price levels rather than how a demand shock is transmitted through prices. In contrast with the first and second scenarios, supply responses are relatively large in each market. To reach a price of $95/cwt for market hogs, an 8% increase over baseline, supply would have to fall by 17%. To reach prices of $75/head for feeder pigs, 23% over baseline, and $45/head for early weaned pigs, 35% over baseline, the supply of each would have to fall by 24% and 22%, respectively. Extrapolating the market hog supply shock—17% decrease—to annual hog slaughter at federally inspected facilities in 2023—116,558,200 head (USDA-NASS, 2023b)—a reduction of around 20,000,000 market hogs would have been required for finishing operations to breakeven. At a rate of 27 pigs weaned per sow per year (PigCHAMP, n.d.), this translates to removing around 750,000 sows from the breeding herd. Using the December 2022 breeding herd as the denominator (USDA-NASS, 2023a), this reduction would be $\frac{750{,}000}{6{,}203{,}500} \approx 12\%$ of the domestic breeding herd.[12] For comparison, one industry analyst estimated that the domestic sow herd would need to be reduced between 6% and 10% to make pork production profitable (Eller, 2024).

The second and third scenarios consider two paths for making hog producers more profitable, increasing demand or decreasing supply. Note that, had wholesale pork demand remained at 2022 levels in 2023, market hog prices would have been $93.90/cwt, close to the breakeven price of $95/cwt. However, while higher demand for wholesale pork would have

pushed market hog prices close to the breakeven price, neither feeder pig prices ($64.54) nor early weaned pig prices ($36.22) would have been close to their breakeven price. This is because market hog prices in 2023 were closer to their breakeven than feeder and early weaned pig prices. While keeping wholesale pork demand at higher 2022 levels could have made finishing operations more profitable in 2023, it would not have been sufficient for farrow-to-feeder or farrow-to-wean operations.

Key to understanding this result is considering how costs changed from 2022 to 2023. Based on Iowa State University's Estimated Livestock Returns – Swine (Schulz, 2024), total costs per pig for farrow-to-wean operations increased from around $41 in 2022 to $44 in 2023. The incremental cost of the nursery phase was consistent at around $28 per pig in both 2022 and 2023, so total costs per pig increased from $69 to $72 from 2022 to 2023 for farrow-to-feeder operations. However, total costs per hundredweight fell from $102 to $97 for wean-to-finish operations and $105 to $92 for feeder-to-finish operations. In sum, production costs increased for farrow-to-wean and farrow-to-feeder operations but decreased for finishing operations. Stronger wholesale pork demand would have attenuated losses for pig producers, but cost increases in pig production offset some of this gain. Because hog production costs fell, strengthening wholesale pork demand would have pushed hog prices close to their breakeven.

Conclusion

The pork supply chain came under intense scrutiny for disruptions due to COVID-19. As conditions normalized, the supply chain evolved in response to new challenges. Plant closures reduced hog processing capacity, and in 2023 pork demand fell. To better understand how the pork supply chain responds to these issues, we derive and estimate a structural model that links markets for hogs, feeder pigs, and early weaned pigs. Our results show that hog processing plant

utilization relative to capacity is a critical issue facing the live-animal segment of the pork supply chain. Building up plant capacity is costly, but there is a positive story from the markets for feeder pigs. Adaptability in the short term requires space to keep pigs. For feeder pigs, the implied own-price elasticity of demand and elasticity of supply are both elastic. Elastic demand or supply is the result of having substitutes or outside options. On the seller side, in particular, operations likely have a multi-week window for marketing while the feeder pigs are in an acceptable weight range.

Using results from the model, we consider counterfactual scenarios for plant capacity in 2020, wholesale pork demand in 2023, and supply in 2023. Without the addition of hog processing plant capacity between 2016 and 2020, hog and pig prices in the second and third quarter of 2020 would have been lower. Had wholesale pork demand remained at 2022 levels in 2023, market hog prices would have been close to the breakeven price for finishing operations; however, feeder pig and early weaned pig prices would have still been far below the breakeven prices for farrow-to-feeder and farrow-to-wean operations. Mirroring this scenario, in 2023, breakeven prices for producers could have been reached through supply shifts in each market. These scenarios highlight the importance of adding processing capacity, limitations of boosting wholesale pork demand, and feasibility of aligning market and breakeven prices through herd management.

Producers seeking to manage risk should note that nursery pig prices are the most sensitive to changes in hog processing plant utilization relative to capacity and wholesale pork demand. Futures contracts exist for market hogs but not feeder pigs or early weaned pigs. Instead, producers can manage price risk through vertical integration and contracting. Because farrow-to-finish operations are vertically integrated, they are only exposed to price risk for

market hogs, which is less sensitive to processing plant utilization, wholesale pork demand, and hog inventories. Contract production is another option to eliminate price risk and may not require changing operation structure.

Policymakers should note that programs designed to increase pork demand may be insufficient to align prices for feeder pigs and early weaned pigs with the breakeven prices for those animals. Looking at supply, aligning prices by reducing the supply of animals would require drastic cuts in pig production. Policies designed to add hog processing capacity are promising because market hog demand—and feeder pig and early weaned pig demand derived from it—is so sensitive to plant utilization. However, excess processing capacity is expensive, so there is a tradeoff between mitigating acute disruptions and operating inefficiently during periods of normal production. Because nurseries can provide a larger marketing window, policymakers aiming to strengthen the pork supply chain should consider incentives to producers for adding nursery capacity.

Two limitations of our analysis are model specification and pig data. Regarding model specification, we model feeder pig and early weaned pig supply from farrowing operations, but nursery-only operations exist and can buy and sell pigs. This could bias our inverse demand estimates for early weaned pigs and supply estimates for feeder pigs if nursery-only operations have different price sensitivities. Regarding pig data, we assume that voluntarily reported pig sales are representative of all transactions for pigs. However, this is impossible to verify. USDA imposes quality measures on reported data, but we have no way to independently verify that the data is representative. There is a separate issue around pigs that are transferred within a system instead of marketed (i.e., inter-farm transfers). While Dahlgran et al. (1996) propose a method for valuing these pigs, we restrict our analysis to pigs that are marketed, which are the residual of

all pigs raised for slaughter, since those are the only pig sales observable to us. Additionally, we exclude formula transactions from our analysis because little is known about their terms.

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	Inverse Demand ($\ln P_t^M$)		Supply ($\ln Q_t^M$)	
Variable	Coefficient	Standard Error	Coefficient	Standard Error
$\ln Q_t^M$	-0.258	0.160		
$\ln WDI_t$	0.656***	0.229		
$Utilization_t$	-1.914***	0.312		
$\ln P_{t-17}^M$			0.072	0.047
$\ln P_{t-22}^M$			0.060	0.042
$\ln P_{t-17}^{CN}$			-0.110***	0.030
$\ln P_{t-22}^{CEW}$			-0.014	0.022
$\ln P_{t-17}^F$			-0.080	0.075
$\ln P_{t-22}^F$			0.212***	0.072
$\ln Q_{t-17}^M$			0.163***	0.043
$\ln Q_{t-22}^M$			0.204***	0.043
$PackerShare_t$			0.134	0.230
Constant	4.996*	2.599	8.856***	0.772
t	0.000	0.000	-0.001***	0.000
February	0.111***	0.037	0.011	0.020
March	0.140***	0.034	-0.003	0.020
April	0.142***	0.045	-0.010	0.025
May	0.247***	0.046	-0.059*	0.031
June	0.279***	0.045	-0.075***	0.027
July	0.271***	0.052	-0.118***	0.028
August	0.199***	0.035	-0.027	0.023
September	0.113***	0.037	-0.009	0.021
October	0.134***	0.032	0.044**	0.018
November	0.049	0.035	0.005	0.021
December	0.050	0.039	-0.027	0.032
2020	-0.196***	0.056	0.016	0.026

** $p < .1$, ** $p < 0.05$, *** $p < 0.01$*

Table 1. Inverse demand and supply coefficient estimates for market hogs. Coefficients are interpreted as the percent change in the dependent variable for a one-percent change in the independent variable excluding deterministic variables.

	Inverse Demand ($\ln P_t^{CN}$)		Supply ($\ln Q_t^{CN}$)	
Variable	Coefficient	Standard Error	Coefficient	Standard Error
$\ln Q_t^{CN}$	-0.426***	0.125		
$\ln P_t^{M}$	1.875***	0.131		
$\ln P_t^{F}$	-0.037	0.176		
$SmallLotShare_t$	-0.594***	0.178		
$\ln P_t^{CN}$			8.942***	3.157
$\ln P_{t-45}^{CN}$			0.990***	0.286
$\ln P_{t-25}^{SOW}$			-0.676**	0.264
$\ln Q_{t-28}^{CN}$			0.094	0.117
PWM_t			-0.673**	0.326
$ContractorShare_t$			-0.277*	0.151
$\ln P_{t-5}^{CEW}$			-5.188***	1.884
Constant	0.000**	0.000	10.888*	5.804
t	-0.057	0.056	0.005**	0.002
February	-0.131**	0.058	0.656*	0.339
March	-0.228***	0.057	0.291	0.243
April	-0.576***	0.061	0.513	0.376
May	-0.885***	0.059	0.818**	0.363
June	-1.094***	0.059	1.405**	0.604
July	-1.132***	0.068	1.390**	0.597
August	-0.792***	0.060	2.357***	0.891
September	-0.642***	0.058	1.635***	0.539
October	-0.367***	0.051	1.308**	0.517
November	-0.103*	0.054	1.173***	0.436
December	-0.238***	0.053	0.120	0.197
2020	-0.426***	0.125	0.500	0.381

** $p < .1$, ** $p < 0.05$, *** $p < 0.01$*

Table 2. Inverse demand and supply coefficient estimates for feeder pigs. Coefficients are interpreted as the percent change in the dependent variable for a one-percent change in the independent variable excluding deterministic variables.

	Inverse Demand ($\ln P_t^{CEW}$)		Supply ($\ln Q_t^{CEW}$)	
Variable	Coefficient	Standard Error	Coefficient	Standard Error
$\ln Q_t^{CEW}$	-1.573***	0.316		
$\ln P_t^M$	1.196***	0.441		
$\ln P_t^F$	-0.576	0.578		
$SmallLotShare_t$	-2.809***	0.700		
$\ln P_{t-20}^{CEW}$			-0.035	0.035
$\ln P_{t-20}^F$			-0.469***	0.142
$\ln P_{t-45}^{CEW}$			0.109***	0.031
$\ln P_{t-20}^{SOW}$			-0.061	0.050
$\ln Q_{t-23}^{CEW}$			0.027	0.026
PWM_t			-0.107***	0.035
$ContractorShare_t$			0.081***	0.022
Constant	17.041***	3.950	8.469***	1.184
t	0.000	0.001	0.001***	0.000
February	-0.273**	0.118	-0.094	0.072
March	-0.488***	0.121	-0.060	0.078
April	-0.669***	0.121	0.011	0.076
May	-0.972***	0.135	-0.050	0.077
June	-1.291***	0.161	-0.040	0.079
July	-1.334***	0.177	0.067	0.076
August	-1.192***	0.176	0.098	0.065
September	-0.931***	0.149	0.061	0.071
October	-0.754***	0.142	0.017	0.070
November	-0.379***	0.114	0.052	0.070
December	-0.136	0.126	-0.013	0.094
2020	0.112	0.106	0.167***	0.053

** $p < .1$, ** $p < 0.05$, *** $p < 0.01$*

Table 3. Inverse demand and supply coefficient estimates for early weaned pigs. Coefficients are interpreted as the percent change in the dependent variable for a one-percent change in the independent variable excluding deterministic variables.

Scenario	Group	Variable	Baseline	Shock	Difference	
Capacity 4/1/2020 - 9/30/2020	Market hogs	Price	$75.75	$61.22	($14.53)	-19%
		Quantity	34,931,335	34,865,853	(65,482)	0%
		Revenue	$2,614,880,590	$2,112,587,593	($502,292,997)	-19%
	Feeder pigs	Price	$35.05	$29.61	($5.44)	-16%
		Quantity	442,014	239,534	(202,480)	-46%
		Revenue	$18,355,399	$8,820,782	($9,534,618)	-52%
	Early weaned pigs	Price	$20.22	$15.64	($4.58)	-23%
		Quantity	1,316,613	1,318,502	1,889	0%
		Revenue	$26,352,459	$20,451,222	($5,901,238)	-22%
Demand 1/1/2023 - 12/31/2023	Market hogs	Price	$87.94	$93.90	$5.96	7%
		Quantity	63,893,764	63,934,767	41,003	0%
		Revenue	$5,584,295,540	$5,966,141,800	$381,846,260	7%
	Feeder pigs	Price	$61.09	$64.54	$3.45	6%
		Quantity	482,532	592,774	110,242	23%
		Revenue	$29,620,304	$39,250,949	$9,630,644	33%
	Early weaned pigs	Price	$33.41	$36.22	$2.81	8%
		Quantity	2,378,185	2,375,928	(2,257)	0%
		Revenue	$74,448,072	$80,673,806	$6,225,734	8%
Quantity 1/1/2023 - 12/31/2023	Market hogs	Price	$87.94	$95.00	$7.06	8%
		Quantity	63,893,764	52,947,390	(10,946,374)	-17%
		Revenue	$5,584,295,540	$5,030,002,065	($554,293,475)	-10%
	Feeder pigs	Price	$61.09	$75.00	$13.91	23%
		Quantity	482,532	367,309	(115,223)	-24%
		Revenue	$29,620,304	$27,548,166	($2,072,138)	-7%
	Early weaned pigs	Price	$33.41	$45.00	$11.59	35%
		Quantity	2,378,185	1,850,591	(527,594)	-22%
		Revenue	$74,448,072	$83,276,599	$8,828,528	12%

Table 4. Results for 2020 capacity, 2023 demand, and 2023 quantity counterfactual scenarios. Prices are the mean over the period, reported in nominal terms; quantities and revenues are totals for the period. Units are in hundredweight for market hogs and head for feeder and early weaned pigs.