Impacts of COVID-19-Induced Labor and Income Shocks on the Broiler Supply Chain

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We use a broiler supply-chain model to examine the impacts of COVID-19-induced labor shortages and income reduction throughout the sector. Results show that the labor shock has negative effects on production throughout the supply chain, causing meat shortages and the average retail price to rise by 11.11%. The income shock lowers both quantities and prices in the supply chain. The combined production effects of both shocks are generally more pronounced, as they reinforce each other. However, retail prices move in opposite directions, with labor shock increasing prices and income shock reducing prices, leading to a 5.44% net increase in the average retail price.

Key words: broiler supply chain, chicken, coronavirus, COVID-19, income, labor

Introduction

Since mid-March 2020, COVID-19 has disrupted economic activities around the world. In the United States, supply chains in meat sectors were hit hard, largely through two channels. First, meat production plants were hot spots for the spread of coronavirus, and the resulting workers’ illness curtailed meat production. Second, workers in many sectors lost jobs due to lockdowns, which caused their income to fall and restaurants to close, leading to a decline in overall meat demand. These two channels caused havoc in the meat supply chain, particularly in the broiler sector, as evident by the euthanasia of millions of chickens due to lack of labor in broiler processing plants.\(^1\) This study analyzes the effects of COVID-19 throughout the broiler supply chain.

The broiler supply chain consists of many layers of operations.\(^2\) The upstream sector begins with integrator-owned feed mills that use corn, soymeal, and other ingredients to supply feed to mostly independent breeder farms and grow-out farms. Breeder farms produce fertilized eggs, which are sold to integrator-owned hatcheries where eggs are incubated for 3 weeks to produce day-old chicks (Chaudhry and Miranda, 2018). The day-old chickens are then moved to independent grow-out farms where chickens take about 6 weeks to grow to maturity (Chaudhry and Miranda, 2018).\(^3\) The integrator exerts market power in buying grown chickens for processing (Hamilton and SUnding, 2020). Grown chickens are transported to processing plants, where different chicken-
meat items (whole chicken; chicken parts consisting of breast meat, dark meat, and wings; and processed chicken) are produced. These products are packaged and sold to wholesalers, retailers, and restaurants in domestic markets and exported to foreign markets. Though labor is employed throughout the production process in the broiler supply chain, operations in the processing plants are the most labor intensive.

Broiler processing plants employ mostly foreign workers and refugees who are not native English speakers, and many of them continue to work, even after becoming infected with the coronavirus, out of necessity, to earn income (Payne, 2020). In addition, crowded working environments and the inability to maintain social distancing allow infected workers to rapidly spread the disease to coworkers. Though President Trump’s executive order kept meatpacking plants operating (Jacobs and Mulvany, 2020) and workers in meat-processing plants are deemed essential (Charlton, 2020; Krisberg, 2020), many of them could not work because of illness or quarantine orders. Consequently, many chicken-processing plants were shuttered or operating below full capacity (Hauser, 2020; Jacobs and Mulvany, 2020; Kevany, 2020).

Because of labor shortages in the chicken-processing plants and the resulting reduction in processing capacity, grown chickens could not be slaughtered in the processing plants. Furthermore, with farm workers also getting sick and farmers finding it uneconomical to feed these chickens, producers had to make the difficult choice to humanely depopulate chicken stocks. Consequently, millions of chickens were culled in many states (see footnote 1). The effects of the reduction in chicken processing and the resulting lower demand for live chickens hemorrhaged through the upstream markets, causing reduced demand for feed, fertilized eggs, and day-old chickens. Furthermore, with fewer chickens processed, the reduced chicken-meat supply and higher prices reverberated throughout the downstream supply chain, all the way to the retail market.

The COVID-19-induced lockdowns and stay-at-home orders caused nonessential U.S. workers to be laid off. The ensuing deep economic recession shrank the second quarter gross domestic product (GDP) by 32.9%. Despite government stimulus, income support, and unemployment insurance payments, total income declined. With a severe income shock to millions of workers and small business owners and the closure of fast-food restaurants and diners, demand for chicken fell amidst heightened food insecurity. Though stay-at-home orders increased chicken demand for home cooking, the overall demand for chicken products declined. The effect of this lower demand rippled through the entire broiler supply chain from downstream to upstream segments.

This study analyzes the COVID-19-induced effects of these two channels—the supply-side shock of fewer workers and the demand-side shock of reduced chicken consumption—on the entire broiler supply chain. Specifically, we examine these effects on the prices and quantities in various segments: feed, fertilized eggs, day-old chickens, live chickens, and various chicken-meat products. In doing so, we can isolate the COVID-19-induced exogenous shocks in the broiler sector on, for example, feed (corn and soymeal) prices and quantities.

Model

The model structuralizes the broiler supply chain described briefly in the introduction and is an expanded version of the model developed by Unveren and Luckstead (2020). Specifically, the new model incorporates (i) labor in various production activities in the supply chain, (ii) dynamics in the hatchery and grow-out segments, and (iii) market power by the integrator in grow-out farms and

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4 By the end of July, more than 43,750 workers in 530 meatpacking and food-processing plants were infected with coronavirus and about 200 workers died as a result of COVID-19 (Nittle, 2020).

5 Previous studies have examined the effects of disease in the poultry sector on production and trade. Wieck, Schlüter, and Britz (2012) used gravity methods to estimate the impacts of avian-influenza-induced trade ban on bilateral trade flows and welfare. Zhou, Li, and Lei (2019) examined the effects of nontariff barriers and avian influenza outbreaks on Chinese poultry exports. Djunaidi and Djunaidi (2007) used a spatial equilibrium model and found that a global outbreak of avian influenza interrupted chicken product trade and increased prices by 9.63%.
retail markets. Below, we present a detailed structure of the various segments and the vertical and horizontal linkages of the broiler supply chain.

**Corn and Soymeal Segment**

The major feed components in the broiler sector are corn and soymeal, which are sold to integrator-owned feed mills. Since corn and soymeal have many end uses, we model supply of corn and soymeal to the feed mills as residual supply functions:

\[
S_{C,t} = \psi_C (p_{C,t})^{\epsilon_C},
\]

\[
S_{SM,t} = \psi_{SM} (p_{SM,t})^{\epsilon_{SM}},
\]

where \(S_{C,t}\) is total supply of corn to broiler integrators in time \(t\), \(p_{C,t}\) is the price of corn, \(\psi_C\) is a scale parameter, \(\epsilon_C\) is the residual-supply elasticity, \(S_{SM,t}\) is total supply of soymeal to broiler integrators in time \(t\), \(p_{SM,t}\) is the price of soymeal, \(\psi_{SM}\) is a scale parameter, and \(\epsilon_{SM}\) is the residual-supply elasticity.

**Feed Mills**

Integrator-owned feed mills use the corn and soymeal to produce feed for the independently-owned breeder and grow-out farms. These feed mills maximize the profit function \((\Pi_{F,t})\)

\[
\Pi_{F,t} = \rho_{F,t} Q_{F,t} - C_F (p_{C,t}, p_{SM,t}, Q_{F,t}),
\]

where \(\rho_{F,t}\) is the transfer price of feed and \(Q_{F,t}\) is quantity of feed. The feed cost function \((C_F (\cdot))\) is given by

\[
C_F (\cdot) = \left(\frac{Q_{F,t}}{A_F}\right)^{\frac{1}{v_F}} \left[\left(\alpha_F^C\right)^{\frac{1}{1+\eta_F}} (p_{C,t})^{\eta_F} + \left(\alpha_F^{SM}\right)^{\frac{1}{1+\eta_F}} (p_{SM,t})^{\eta_F}\right]^{-\frac{1+\eta_F}{\eta_F}},
\]

where \(A_F\) is the productivity parameter, \(v_F\) is the returns-to-scale parameter, \(\alpha_F^C\) and \(\alpha_F^{SM}\) are share parameters, and \(\eta_F\) is the constant elasticity of substitution (CES) parameter. The first-order condition of profit maximization with respect to \(Q_{F,t}\) is solved to obtain feed supply as a function of the output (feed) and input (corn and soymeal) prices:

\[
Q_{F,t} = \left(\frac{1}{\rho_{F,t} v_F (A_F)^{\frac{1}{v_F}}} \left[\left(\alpha_F^C\right)^{\frac{1}{1+\eta_F}} (p_{C,t})^{\eta_F} + \left(\alpha_F^{SM}\right)^{\frac{1}{1+\eta_F}} (p_{SM,t})^{\eta_F}\right]\right)^\frac{v_F}{\eta_F^{v_F-1}}.
\]

6 The transfer prices for feed, day-old chickens (DOCs), and chickens for further processing are prices transacted between integrator segments. The contracts between the integrators and grow-out farms are involved and clearly identify terms and conditions for various aspects of how birds are raised, such as DOCs, feed, and veterinary requirements (Vukina and Leegommonchai, 2006).
From Shepard’s lemma, the input demand functions for corn ($D^F_{C,i}$) and soymeal ($D^F_{SM,i}$) are respectively derived as

\begin{align}
D^F_{C,i} &= \frac{\partial C_F(\cdot)}{\partial p_{C,i}} = \left(\frac{Q_{F,i}}{A_F}\right)^{\frac{1}{\nu}} \left(\left(\alpha^C_F\right)^{\frac{1}{\nu+\eta_F}} (p_{C,i})^{\frac{\eta_F}{\nu+\eta_F}} + \left(\alpha^F_SM\right)^{\frac{1}{\nu+\eta_F}} (p_{SM,i})^{\frac{\eta_F}{\nu+\eta_F}}\right)^{\frac{1}{\eta_F}} \\
D^F_{SM,i} &= \frac{\partial C_F(\cdot)}{\partial p_{SM,i}} = \left(\frac{Q_{F,i}}{A_F}\right)^{\frac{1}{\nu}} \left(\left(\alpha^C_F\right)^{\frac{1}{\nu+\eta_F}} (p_{C,i})^{\frac{\eta_F}{\nu+\eta_F}} + \left(\alpha^F_SM\right)^{\frac{1}{\nu+\eta_F}} (p_{SM,i})^{\frac{\eta_F}{\nu+\eta_F}}\right)^{\frac{1}{\eta_F}} \times \\
&\quad \left(\alpha^F_SM\right)^{\frac{1}{\nu+\eta_F}} (p_{SM,i})^{\frac{1}{\nu+\eta_F}} .
\end{align}

**Breeder**

Independently-owned breeder farmers use feed and labor to produce fertilized eggs that are sold to integrator-owned hatcheries. The profit function for breeders ($\Pi_{E,i}$) is

\begin{align}
\Pi_{E,i} &= p_{E,i} Q_{E,i} - C_E(p_{F,i}, p_{L,i}, Q_{E,i}) ,
\end{align}

where $p_{E,i}$ is the price of fertilized eggs and $Q_{E,i}$ is the quantity of fertilized eggs. The breeder cost function ($C_E(\cdot)$) is

\begin{align}
C_E(\cdot) &= \left(\frac{Q_{E,i}}{A_E}\right)^{\frac{1}{\nu_E}} \left[\left(\alpha^E_F\right)^{\frac{1}{\nu+\eta_E}} (p_{F,i})^{\frac{\eta_E}{\nu+\eta_E}} + \left(\alpha^E_L\right)^{\frac{1}{\nu+\eta_E}} (p_{L,i})^{\frac{\eta_E}{\nu+\eta_E}}\right]^{\frac{1+\eta_E}{\eta_E}} ,
\end{align}

where $\alpha^E_F$ and $\alpha^E_L$ are share parameters, $p_{L,i}$ is the hired-labor wage rate, $A_E$ is the productivity parameter, and $\nu_E$ is the returns-to-scale parameter. The first-order condition of profit maximization with respect to $Q_{E,i}$ is solved to obtain fertilized egg supply as a function of output (egg) and input (feed and hired labor) prices:

\begin{align}
Q_{E,i} &= \left(\frac{1}{p_{E,i} v_E} (Q_{E,i})^{\frac{1}{\nu_E}}\right)^{\frac{1}{\nu_E}} \left[\left(\alpha^E_F\right)^{\frac{1}{\nu+\eta_E}} (p_{F,i})^{\frac{\eta_E}{\nu+\eta_E}} + \left(\alpha^E_L\right)^{\frac{1}{\nu+\eta_E}} (p_{L,i})^{\frac{\eta_E}{\nu+\eta_E}}\right]^{\frac{1+\eta_E}{\eta_E}} .
\end{align}

Differentiating the cost function with respect to the input prices yields the input demand functions for feed ($D^E_{F,i}$) and hired labor ($D^E_{L,i}$), respectively:

\begin{align}
D^E_{F,i} &= \frac{\partial C_E(\cdot)}{\partial p_{F,i}} = \left(\frac{Q_{E,i}}{A_E}\right)^{\frac{1}{\nu_E}} \left[\left(\alpha^E_F\right)^{\frac{1}{\nu+\eta_E}} (p_{F,i})^{\frac{\eta_E}{\nu+\eta_E}} + \left(\alpha^E_L\right)^{\frac{1}{\nu+\eta_E}} (p_{L,i})^{\frac{\eta_E}{\nu+\eta_E}}\right]^{\frac{1}{\eta_E}} \times \\
&\quad \left(\alpha^E_F\right)^{\frac{1}{\nu+\eta_E}} (p_{F,i})^{\frac{1}{\nu+\eta_E}} ,
\end{align}

\begin{align}
D^E_{L,i} &= \frac{\partial C_E(\cdot)}{\partial p_{L,i}} = \left(\frac{Q_{E,i}}{A_E}\right)^{\frac{1}{\nu_E}} \left[\left(\alpha^E_F\right)^{\frac{1}{\nu+\eta_E}} (p_{F,i})^{\frac{\eta_E}{\nu+\eta_E}} + \left(\alpha^E_L\right)^{\frac{1}{\nu+\eta_E}} (p_{L,i})^{\frac{\eta_E}{\nu+\eta_E}}\right]^{\frac{1}{\eta_E}} \times \\
&\quad \left(\alpha^E_L\right)^{\frac{1}{\nu+\eta_E}} (p_{L,i})^{\frac{1}{\nu+\eta_E}} .
\end{align}

**Hatchery**

Integrator-owned chick producers purchase fertilized eggs from independent breeder farms. At the hatcheries, a batch of eggs yield a batch of DOCs. The incubation period is about 3 weeks. Since
producers have to make decisions about how many eggs to buy without knowing the price they will receive for DOCs due to uncertainty in the production process and market conditions, we model this production process in a dynamic framework following Chaudhry and Miranda (2018).\(^7\) The profit function for hatchery \(\Pi_{H,t}\) is

\[
\Pi_{H,t+1} = \tilde{\rho}_{H,t+1} Q_{H,t+1} - p_{E,t} D^H_{E,t} - C_H \left( D^H_{E,t} \right),
\]

where \(Q_{H,t+1} = k_H D^H_{E,t}, \) \(0 < k_H < 1,\) indicating that the number of eggs \(\left( D^H_{E,t} \right)\) is converted to the number of DOCs \(\left( Q_{H,t+1} \right)\) with a conversion factor \(k_H, \) \(\tilde{\rho}_{H,t+1} = E_t \left( \rho_{H,t+1} \right)\) is the expected transfer price of DOCs in period \(t+1,\)\(^8\) \(C_H (\cdot) = \left( \frac{p_{H,t}}{\lambda_H} \right)^{1/\nu_H} \) is the cost function accounting for other input costs in producing DOCs, \(A_H\) is the productivity parameter, and \(\nu_H\) is the returns-to-scale parameter. One time period is 3 weeks (i.e., \(\Delta t = 3\) weeks). The first-order condition of profit maximization with respect to \(Q_{H,t+1}\) yields

\[
\frac{\partial \Pi_{H,t+1}}{\partial Q_{H,t+1}} = \tilde{\rho}_{H,t+1} - \frac{p_{E,t}}{k_H} - \left( \frac{Q_{H,t+1}}{A_H k_H} \right)^{\frac{1}{\nu_H}} \left( \frac{1}{\nu_H A_H k_H} \right) = 0.
\]

Solving for \(Q_{H,t}\) obtains supply as a function of the output and input prices:

\[
Q_{H,t+1} = (A_H k_H)^{\frac{\rho_H}{\nu_H}} \left( \tilde{\rho}_{H,t+1} - \frac{p_{E,t}}{k_H} \right)^{\frac{1}{\nu_H}} \left( \frac{\nu_H}{\beta_H} \right)^{\frac{\nu_H}{\nu_H - \beta_H}}.
\]

Input demand is given by

\[
D^H_{E,t} = \frac{Q_{H,t+1}}{k_H}.
\]

**Grow-Out Farms**

Independent grow-out farms raise DOCs to full-grown broiler chickens for sales to processors. This growth process takes about 6 weeks. At the time of input (DOC) purchase, growers face uncertainty in relative production performance and market condition.\(^9\) With the production time lag and uncertainty, the production process is modeled in a dynamic framework. The profit function for a grow-out farmer, \(\Pi_{G,t+2}\), is

\[
\Pi_{G,t+2} = \tilde{\rho}_{G,t+2} Q_{G,t+2} - \rho_{H,t} D^G_{H,t} - C_G \left( \rho_{F,t}, p_{L,t}, D^G_{H,t} \right),
\]

where \(Q_{G,t+2} = k_G D^G_{H,t}, \) \(0 < k_G < 1,\) implying that the number of DOCs \(\left( D^G_{H,t} \right)\) is converted into the number of grown broilers \(\left( Q_{G,t+2} \right)\) with a conversion factor \(k_G;\) and \(\tilde{\rho}_{G,t+2} = E_t \left( \rho_{G,t+2} \right)\) is the expected price of grown broiler chickens in period \(t+2.\) The cost function, \(C_G (\cdot),\) which accounts for the cost of feed and labor inputs, is

\[
C_G (\cdot) = \left( \frac{D^G_{H,t}}{A_G} \right)^{\frac{1}{\nu_G}} \left[ \left( \alpha^l_G \right)^{\frac{1}{\tau + \eta_G}} \left( \rho_{F,t} \right)^{\frac{\eta_G}{\tau + \eta_G}} + \left( \alpha^l_G \right)^{\frac{1}{\tau + \eta_G}} \left( p_{L,t} \right)^{\frac{\eta_G}{\tau + \eta_G}} \right]^{\frac{1 - \eta_G}{\eta_G}},
\]

\(^7\) See Chavas (1999) for similar modeling of dynamics in hatchery and grow-out farms.

\(^8\) Dolgui, Ivanov, and Sokolov (2018) and Rosales et al. (2019) analyzed impacts of risk on broiler supply chain management.

\(^9\) Grow-out farms agree to a payment structure that depends on relative performance due to the growers’ feed conversion ratio, which is \textit{a priori} unknown to the grow-out farms (Hamilton and Sunding, 2020).
where $A_G$ is the productivity parameter, $\nu_G$ is the returns-to-scale parameter, $\alpha_G^F$ and $\alpha_G^L$ are share parameters, and $\eta_G$ is the CES parameter. Since $\Delta t = 3$ weeks, the lag between $t$ and $t + 2$ is 6 weeks. The first-order condition of profit maximization with respect to $Q_{G,t+2}$ yields

$$\frac{\partial \Pi_{G,t+2}}{\partial Q_{G,t+2}} = \bar{p}_{G,t+2} - \frac{\rho_{H,t}}{k_G} - \left( \frac{Q_{G,t+2}}{A_G k_G} \right)^{\frac{1}{\nu_G} - 1} \times$$

$$\left[ \left( \alpha_G^F \right)^{\frac{\eta_G}{1 + \eta_G}} \left( \rho_{F,t} \right)^{\frac{\eta_G}{1 + \eta_G}} + \left( \alpha_G^L \right)^{\frac{\eta_G}{1 + \eta_G}} \left( p_{L,t} \right)^{\frac{\eta_G}{1 + \eta_G}} \right]^{\frac{1 + \eta_G}{\eta_G}} = 0.$$  

Solving for $Q_{G,t}$ yields supply as a function of the output price and input prices:

$$Q_{G,t+2} = \left( A_G k_G \right)^{\frac{1}{1-\nu_G}} \left( \bar{p}_{G,t+2} - \frac{\rho_{H,t}}{k_G} \right)^{\frac{\nu_G}{1-\nu_G}} \times$$

$$\left( \beta_G \left[ \left( \alpha_G^F \right)^{\frac{\eta_G}{1 + \eta_G}} \left( \rho_{F,t} \right)^{\frac{\eta_G}{1 + \eta_G}} + \left( \alpha_G^L \right)^{\frac{\eta_G}{1 + \eta_G}} \left( p_{L,t} \right)^{\frac{\eta_G}{1 + \eta_G}} \right]^{\frac{1 + \eta_G}{\eta_G}} \right)^{\frac{\nu_G}{1-\nu_G}}.$$  

Demand for DOCs is

$$D_{H,t}^G = \frac{Q_{G,t+2}}{k_G}.$$  

Input demand functions for feed ($D_{F,t}^G$) and labor ($D_{L,t}^G$) are, respectively,

$$D_{F,t}^G = \frac{\partial C_G(\cdot)}{\partial p_{F,t}} = \left( \frac{D_{H,t}^G}{A_G} \right)^{\frac{\nu_G}{1-\nu_G}} \left( \left( \alpha_G^F \right)^{\frac{1}{1+\eta_G}} \left( \rho_{F,t} \right)^{\frac{1}{1+\eta_G}} + \left( \alpha_G^L \right)^{\frac{1}{1+\eta_G}} \left( p_{L,t} \right)^{\frac{1}{1+\eta_G}} \right)^{\frac{1}{\eta_G}} \times$$

$$\left( \alpha_G^F \right)^{\frac{1}{1+\eta_G}} \left( \rho_{F,t} \right)^{\frac{1}{1+\eta_G}},$$

$$D_{L,t}^G = \frac{\partial C_G(\cdot)}{\partial p_{L,t}} = \left( \frac{D_{H,t}^G}{A_G} \right)^{\frac{\nu_G}{1-\nu_G}} \left( \left( \alpha_G^F \right)^{\frac{1}{1+\eta_G}} \left( \rho_{F,t} \right)^{\frac{1}{1+\eta_G}} + \left( \alpha_G^L \right)^{\frac{1}{1+\eta_G}} \left( p_{L,t} \right)^{\frac{1}{1+\eta_G}} \right)^{\frac{1}{\eta_G}} \times$$

$$\left( \alpha_G^L \right)^{\frac{1}{1+\eta_G}} \left( p_{L,t} \right)^{\frac{1}{1+\eta_G}}.$$  

Processing Plants

The broiler sector is impacted by market power exerted by integrator-owned processing plants both in purchasing the broilers and selling the retail products. To model this market power, the integrator in the processing segment is modeled as one representative firm, represented by lowercase letters, as opposed to the aggregate production process in the above segments, represented by uppercase letters. Then, to obtain total production in the processing segment, we multiply the representative firm’s production by total number of integrators.

Broilers bought from the grow-out farmers are used to produce three different chicken products: whole chickens, chicken parts (breast meat, wings, and dark meat), and chickens slaughtered for ready-to-eat processing.

10 See Ollinger, MacDonald, and Madison (2005) for analysis related to the effect of technological change on the broiler market.
Whole Chickens

The integrator-owned firm involved in the production of whole chickens exercises market power both in the purchase of grown broilers and sales of whole chickens in the retail market. The profit function of whole chicken production, \( \pi_{W,t} \), is

\[
\pi_{W,t} = p_{W,t} (Q_{W,t}) q_{W,t} - p_{G,t} (D_{G,t}^W) q_{G,t}^W - p_{L,t} d_{L,t}^W,
\]

where \( p_{W,t} \) is price per pound of whole chickens, \( Q_{W,t} \) is the total poundage of whole chickens produced by all firms, \( q_{W,t} \) is the total poundage of whole chickens produced by the representative integrator, \( D_{G,t}^W \) is total demand for grown chickens by all firms, \( d_{L,t}^W \) is total demand for grown chickens by the representative integrator, and \( d_{L,t}^W \) is demand for labor by the representative integrator. The production function is

\[
q_{W,t} = A_W \left[ \alpha_W^G \left( d_{G,t}^W \right)^{\eta_W} + \alpha_W^L \left( d_{L,t}^W \right)^{\eta_W} \right]^{\eta_W^{-1}},
\]

where \( A_W \) is the productivity parameter, \( \alpha_W^G \) and \( \alpha_W^L \) are share parameters with \( \alpha_W^G + \alpha_W^L = 1 \), \( \eta_W \) is the CES parameter, and \( \eta_W \) is the returns-to-scale parameter. Under Cournot competition, profit maximization with respect to inputs \( d_{G,t}^W \) and \( d_{L,t}^W \) results in

\[
\frac{\partial \pi_{W,t}}{\partial d_{G,t}^W} = p_{W,t} \left( 1 + \frac{1}{N_W} \frac{1}{\epsilon_W} \right) \frac{\partial q_{W,t}}{\partial d_{G,t}^W} - p_{G,t} \left( 1 + \frac{1}{N_R} \frac{1}{\epsilon_G} \right) = 0,
\]

\[
\frac{\partial \pi_{W,t}}{\partial d_{L,t}^W} = p_{W,t} \left( 1 + \frac{1}{N_W} \frac{1}{\epsilon_W} \right) \frac{\partial q_{W,t}}{\partial d_{L,t}^W} - p_{L,t} = 0,
\]

where \( N_W \) is the number of integrators nationally, \( \epsilon_W = \frac{p_{W,t}}{p_{G,t} \frac{\partial Q_{W,t}}{\partial p_{W,t}}} \) is the elasticity of demand for whole chicken, \( N_R \) is the average number of firms regionally, \( \epsilon_G = \frac{p_{G,t}}{p_{G,t} \frac{\partial Q_{G,t}}{\partial p_{G,t}}} \) is the elasticity of supply of grown chickens, \( \frac{\partial q_{W,t}}{\partial d_{G,t}^W} = A_W \eta_W \left[ \alpha_W^G \left( d_{G,t}^W \right)^{\eta_W} + \alpha_W^L \left( d_{L,t}^W \right)^{\eta_W} \right]^{\eta_W^{-1}} \), and

\[
\frac{\partial q_{W,t}}{\partial d_{L,t}^W} = A_W \eta_W \left[ \alpha_W^G \left( d_{G,t}^W \right)^{\eta_W} + \alpha_W^L \left( d_{L,t}^W \right)^{\eta_W} \right]^{\eta_W^{-1}} \alpha_W^L \left( d_{L,t}^W \right)^{\eta_W^{-1}}. \]

Note that \( N_W \) is different from \( N_R \) because chicken product sales occur nationally but broiler purchases occur regionally because live birds do not transport well over long distances.

Chicken Parts

One chicken yields \( w \) pounds of chicken breasts, \( Q_{Br,t} \); \( \gamma \) pounds of chicken wings, \( Q_{Wi,t} \); and \( \mu \) pounds of dark meat, \( Q_{D,t} \), which implies the following relationships:

\[
Q_{Br,t} = w Q_{Pt,t}, Q_{Wi,t} = \gamma Q_{Pt,t}, \text{ and } Q_{D,t} = \mu Q_{Pt,t}.
\]

Total poundage of chicken parts, \( Q_{Pt,t} \), is

\[
Q_{Pt,t} = Q_{Br,t} + Q_{Wi,t} + Q_{D,t}.
\]

Total revenue for chicken parts is obtained by multiplying quantity by price:

\[
p_{Pt,t} Q_{Pt,t} = p_{Br,t} Q_{Br,t} + p_{Wi,t} Q_{Wi,t} + p_{D,t} Q_{D,t},
\]

where \( p_{Pt,t} \) is the price index for parts, \( p_{Br,t} \) is price per pound of chicken breast, \( p_{Wi,t} \) is price of per pound of chicken wings, and \( p_{D,t} \) is price per pound of chicken dark meat. We
can define the price index for parts by substituting equation (28) into \( p_{P,t}Q_{P,t} \), which yields
\[ p_{P,t}Q_{P,t} = \left( \omega p_{Br,t} + \gamma p_{Wi,t} + \mu p_{D,t} \right) Q_{P,t} \]. Then, the price index for chicken parts \( p_{P,t} \) is
\begin{equation}
(31) \quad p_{P,t} = \omega p_{Br,t} + \gamma p_{Wi,t} + \mu p_{D,t}.
\end{equation}

Similar to the production process for whole chickens, the integrator in chicken parts production exerts market power in both the input and output markets. The major inputs in the production of chicken parts are broilers bought from the grow-out farms and labor. The profit function for chicken parts, \((\pi_{P,t})\), is
\begin{equation}
(32) \quad \pi_{P,t} = p_{P,t} \left( Q_{P,t} \right) q_{P,t} - p_{G,t} \left( D_{G,t}^P \right) d_{G,t}^P - p_{L,t} d_{L,t}^P,
\end{equation}
where \( q_{P,t} \) is the total poundage of whole chickens produced by the representative integrator, \( D_{G,t}^P \) is total demand for grown chickens, \( d_{G,t}^P \) is total demand for grown chickens by the representative integrator, and \( d_{L,t}^P \) is demand for labor by the representative integrator. The production function is
\begin{equation}
(33) \quad q_{P,t} = A_P \left[ \alpha_P^G \left( d_{G,t}^P \right)^{\eta_P} + \alpha_P^L \left( d_{L,t}^P \right)^{\eta_P} \right]^{\nu_P},
\end{equation}
where \( A_P \) is the productivity parameter, \( \alpha_P^G \) and \( \alpha_P^L \) are share parameters with \( \alpha_P^G + \alpha_P^L = 1 \). \( \eta_P \) is the CES parameter, and \( \nu_P \) is the returns-to-scale parameter. Profit maximization under Cournot competition leads to
\begin{equation}
(34) \quad \frac{\partial \pi_{P,t}}{\partial d_{G,t}^P} = p_{P,t} \left( 1 + \frac{1}{N_N} \frac{1}{e_P} \right) \frac{\partial q_{P,t}}{\partial d_{G,t}^P} - p_{G,t} \left( 1 + \frac{1}{N_R} \frac{1}{e_G} \right) = 0,
\end{equation}
\begin{equation}
(35) \quad \frac{\partial \pi_{P,t}}{\partial d_{L,t}^P} = p_{P,t} \left( 1 + \frac{1}{N_N} \frac{1}{e_P} \right) \frac{\partial q_{P,t}}{\partial d_{L,t}^P} - p_{L,t} = 0,
\end{equation}
where \( e_P = \frac{p_{P,t}}{q_{P,t}} \frac{\partial q_{P,t}}{\partial p_{P,t}} \) is the elasticity of demand for chicken parts, \( e_G = \frac{p_{G,t}}{d_{G,t}^P} \frac{\partial D_{G,t}^P}{\partial p_{G,t}} \) is the elasticity of supply of grown chickens, \( \frac{\partial q_{P,t}}{\partial d_{G,t}^P} = A_P \nu_P \left[ \alpha_P^G \left( d_{G,t}^P \right)^{\eta_P} + \alpha_P^L \left( d_{L,t}^P \right)^{\eta_P} \right]^{\nu_P-1} \alpha_P^G \left( d_{G,t}^P \right)^{\eta_P-1} \), and \( \frac{\partial q_{P,t}}{\partial d_{L,t}^P} = A_P \nu_P \left[ \alpha_P^G \left( d_{G,t}^P \right)^{\eta_P} + \alpha_P^L \left( d_{L,t}^P \right)^{\eta_P} \right]^{\nu_P-1} \alpha_P^L \left( d_{L,t}^P \right)^{\eta_P-1} \).

Chickens Processed for the Ready-to-Eat Segment

For production of ready-to-eat processed products, broilers are first slaughtered and dressed and then processed into ready-to-eat products. Since the integrator owns both the slaughtering segment and the ready-to-eat processing segment, in the slaughter segment, market power is only exerted upstream in the input market (purchasing live birds from grow-out farms). The profit function for chickens slaughtered for further processing, \((\pi_{FP,t})\), is
\begin{equation}
(36) \quad \pi_{FP,t} = \rho_{FP,t}q_{FP,t} - p_{G,t} \left( D_{G,t}^{FP} \right) d_{G,t}^{FP} - p_{L,t} d_{L,t}^{FP},
\end{equation}
where \( \rho_{FP,t} \) is a transfer price for further processing, \( q_{FP,t} \) is the total poundage of whole chickens produced by the representative integrator, \( D_{G,t}^{FP} \) is total demand for grown chickens for whole chicken production, \( d_{G,t}^{FP} \) is total demand for grown chickens for whole chicken production by the representative integrator, and \( d_{L,t}^{FP} \) is demand for labor for whole chicken production by the representative integrator. The production function is
\begin{equation}
(37) \quad q_{FP,t} = A_{FP} \left[ \alpha_{FP}^G \left( d_{G,t}^{FP} \right)^{\eta_{FP}} + \alpha_{FP}^L \left( d_{L,t}^{FP} \right)^{\eta_{FP}} \right]^{\nu_{FP}}.
\end{equation}
where $A_{FP}$ is the productivity, $\alpha^G_{FP}$ and $\alpha^L_{FP}$ are share parameters with $\alpha^G_{FP} + \alpha^L_{FP} = 1$, $\eta_{FP}$ is the CES parameter, and $\nu_{FP}$ is the returns-to-scale parameter. Profit maximization under Cournot competition leads to

$$\frac{\partial \pi_{FP,i}}{\partial d_{G,i}^{FP}} = \rho_{FP,i} \frac{\partial q_{FP,i}}{\partial d_{G,i}^{FP}} - p_{G,i} \left(1 + \frac{1}{N_R} \varepsilon_G \right) = 0, \tag{38}$$

$$\frac{\partial \pi_{FP,i}}{\partial d_{L,i}^{FP}} = \rho_{FP,i} \frac{\partial q_{FP,i}}{\partial d_{L,i}^{FP}} - p_{L,i} = 0, \tag{39}$$

where $\varepsilon_G = \frac{p_{G,i}}{D_{G,i}^{FP}} \frac{\partial D_{G,i}^{FP}}{\partial p_{G,i}}$ is the elasticity of supply of grown chickens,

$$\frac{\partial q_{FP,i}}{\partial d_{G,i}^{FP}} = A_{FP} \nu_{FP} \left[ \alpha^G_{FP} \left(d_{G,i}^{FP}\right)^{\eta_{FP}} + \alpha^L_{FP} \left(d_{L,i}^{FP}\right)^{\eta_{FP}} \right]^{\frac{\nu_{FP} - 1}{\nu_{FP}}} \alpha^G_{FP} \left(d_{G,i}^{FP}\right)^{\eta_{FP}-1}, \tag{40}$$

and

$$\frac{\partial q_{FP,i}}{\partial d_{L,i}^{FP}} = A_{FP} \nu_{FP} \left[ \alpha^G_{FP} \left(d_{G,i}^{FP}\right)^{\eta_{FP}} + \alpha^L_{FP} \left(d_{L,i}^{FP}\right)^{\eta_{FP}} \right]^{\frac{\nu_{FP} - 1}{\nu_{FP}}} \alpha^L_{FP} \left(d_{L,i}^{FP}\right)^{\eta_{FP}-1}. \tag{41}$$

### Ready-to-Eat Processing Segment

Again, since the integrator owns the upstream segment (slaughtering broilers for further processing in the read-to-eat segment), market power is only exerted downstream in the retail market. The ready-to-eat processing segment utilizes dressed broilers from the further processing segment and labor to produce ready-to-eat processed chicken products. The profit function for ready-to-eat plants ($\pi_{RE,i}$) is

$$\pi_{RE,i} = p_{RE,i} (Q_{RE,i}) q_{RE,i} - \rho_{FP,i} d_{FP,i}^{RE} - p_{L,i} d_{L,i}^{RE}, \tag{42}$$

where $p_{RE,i}$ is price per pound of ready-to-eat products, $Q_{RE,i}$ is the total poundage of ready-to-eat products produced, $q_{RE,i}$ is the total poundage of ready-to-eat products produced by the representative integrator, $\rho_{FP,i}$ is the transfer price of the chickens slaughtered for further processing, $d_{FP,i}^{RE}$ is demand for chickens slaughtered for further processing by the representative integrator, and $d_{L,i}^{RE}$ is demand for labor for ready-to-eat product produced by the representative integrator. The production function is

$$q_{RE,i} = A_{RE} \left[ \alpha^G_{RE} \left(d_{FP,i}^{RE}\right)^{\eta_{RE}} + \alpha^L_{RE} \left(d_{L,i}^{RE}\right)^{\eta_{RE}} \right]^{\frac{\nu_{RE} - 1}{\nu_{RE}}}, \tag{43}$$

where $A_{RE}$ is the productivity, $\alpha^G_{RE}$ and $\alpha^L_{RE}$ are share parameters where $\alpha^G_{RE} + \alpha^L_{RE} = 1$, $\eta_{RE}$ is the CES parameter, and $\nu_{RE}$ is the returns to scale. Profit maximization under Cournot competition leads to

$$\frac{\partial \pi_{RE,i}}{\partial d_{FP,i}^{RE}} = p_{RE,i} \left(1 + \frac{1}{N_N} \varepsilon_{RE} \right) \frac{\partial q_{RE,i}}{\partial d_{FP,i}^{RE}} - \rho_{FP,i} = 0, \tag{44}$$

$$\frac{\partial \pi_{RE,i}}{\partial d_{L,i}^{RE}} = p_{RE,i} \left(1 + \frac{1}{N_N} \varepsilon_{RE} \right) \frac{\partial q_{RE,i}}{\partial d_{L,i}^{RE}} - p_{L,i} = 0, \tag{45}$$

where $\varepsilon_{RE} = \frac{p_{RE,i}}{Q_{RE,i}} \frac{\partial Q_{RE,i}}{\partial p_{RE,i}}$ is the elasticity of demand for ready-to-eat products,

$$\frac{\partial q_{RE,i}}{\partial d_{FP,i}^{RE}} = A_{RE} \nu_{RE} \left[ \alpha^G_{RE} \left(d_{FP,i}^{RE}\right)^{\eta_{RE}} + \alpha^L_{RE} \left(d_{L,i}^{RE}\right)^{\eta_{RE}} \right]^{\frac{\nu_{RE} - 1}{\nu_{RE}}} \alpha^G_{RE} \left(d_{FP,i}^{RE}\right)^{\eta_{RE}-1}, \tag{46}$$
where fertilized egg supply, \( Q (51) \), is used by both breeders and grow-out farms, a horizontal linkage occurs in the feed segment.

\[
\frac{\partial q_{RE,i}}{\partial d_{RE,i}} = A_{RE} v_{RE} \left[ \alpha_{RE}^F \left( d_{FP,i} \right)^{\eta_{RE}} + \alpha_{RE}^L \left( d_{L,i} \right)^{\eta_{RE}} \right]^{\frac{1}{1 + \eta_{RE}}} \alpha_{RE}^L \left( d_{L,i} \right)^{\eta_{RE} - 1}.
\]

Market-Clearing Conditions

The upstream market of this supply chain begins with corn and soybean feed components. The market-clearing conditions for these two raw inputs are

\[
S_C (p_{C,i}) = D_C^F (p_{C,i}),
\]

\[
S_{SM} (p_{SM,i}) = D_{SM}^F (p_{SM,i}),
\]

where \( S_C (\cdot) \) and \( S_{SM} (\cdot) \) are residual corn and soybean supply functions facing the broiler sector and \( D_C^F (\cdot) \) and \( D_{SM}^F (\cdot) \) are the corn and soy meal demand functions obtained above.

The feed price is determined by the market-clearing condition

\[
Q_F (p_{F,i}; p_{C,i}, p_{SM,i}) = D_F^B (p_{F,i}) + D_F^P (p_{F,i}; p_{H,i}),
\]

where feed supply, \( Q_F (\cdot, \cdot) \), is a function of the feed transfer price and corn and soy meal input prices, and \( D_F^B (\cdot) \) and \( D_F^P (\cdot; \cdot) \) are demand for feed by breeders and by grow-out farmers, respectively. As feed is used by both breeders and grow-out farms, a horizontal linkage occurs in the feed segment.

The market-clearing condition for fertilized eggs in the breeder segment is

\[
Q_E (p_{E,i}; p_{F,i}) = D_E^H (p_{E,i}),
\]

where fertilized egg supply, \( Q_E (\cdot, \cdot) \), is a function of fertilized egg price and feed transfer price and \( D_E^H (\cdot) \) is demand for fertilized eggs by hatcheries. In general, vertical linkages occur as output price in an upstream segment becomes input price in the immediate downstream segment. For example, \( p_F \) is the output price in feed production but the input price in fertilized egg production. The market-clearing condition for DOCs in the hatchery segment is

\[
Q_H (p_{H,i}; p_{E,i}) = D_H^G (p_{H,i}; p_{F,i}, p_{L,i}),
\]

where DOC supply, \( Q_H (\cdot, \cdot) \), is a function of the DOC transfer price and fertilized egg price and \( D_H^G (\cdot; \cdot) \) is the demand function for DOCs by grow-out farms. The market-clearing condition for fully grown chickens in the grow-out segment is

\[
Q_G (p_{G,i}; p_{H,i}, p_{F,i}) = D_G^W (p_{G,i}; p_{L,i}) + D_G^P (p_{G,i}; p_{L,i}) + D_{FP}^G (p_{G,i}; p_{L,i}),
\]

where live-chicken supply, \( Q_G (\cdot, \cdot) \), is a function of live-chicken price and DOC and feed transfer prices and \( D_G^W (\cdot; \cdot) \), \( D_G^P (\cdot; \cdot) \), and \( D_{FP}^G (\cdot; \cdot) \) are demand for live chickens by three processing segments: whole chicken, chicken parts (breast meat, dark meat, and wings), and further processing, respectively. Since these three processing segments use live chickens, a horizontal linkage exists at this stage of the supply chain.

The market-clearing condition for chickens slaughtered for further processing is

\[
Q_{FP} (p_{FP,i}; p_{G,i}, p_{L,i}) = D_{FP}^E (p_{FP,i}; p_{L,i}),
\]

where \( Q_{FP} (\cdot, \cdot) \) is the supply function of dressed chickens and \( D_{FP}^E (\cdot; \cdot) \) is the demand for dressed chickens for ready-to-eat meat preparation, such as chicken nuggets.
Severe labor shortages in the broiler supply chain led to an increase in the wage rate. Consequently, these labor shortages are captured in the demand functions explicitly through the wage rate. The market-clearing condition for labor is

\[ S_L(p_{L,i}) = D^E_L(p_{L,i}; \rho_{F,i}) + D^G_L(p_{L,i}; P_{H,i}, P_{F,i}) + D^W_L(p_{L,i}; p_{G,i}) + D^P_L(p_{L,i}; P_{G,i}) + D^RE_L(p_{L,i}; P_{F,RE}), \]

where \( S_L(\cdot) \) is labor supply for chicken processing and \( D^E_L(\cdot; \cdot), D^G_L(\cdot; \cdot), D^W_L(\cdot; \cdot), D^P_L(\cdot; \cdot), D^RE_L(\cdot; \cdot) \) are demand for labor in various production segments.

The market prices for the final products are determined by the following market-clearing conditions:

\[ Q_k(p_{k,i}; P_{G,i}, P_{L,i}) = H^U_k(p_{k,i}; I^U_t) + H^M_k(p_{k,i}; I^M_t) + H^C_k(p_{k,i}; I^C_t) + H^R_k(p_{k,i}; I^R_t), \]

where the supply function, \( Q_k(\cdot; \cdot) \), of a particular meat \( k \) \((k = W, BR, Wi, D, RE)\) is a function of output price and input prices for live birds and labor and

\[ H^h_k(p_{k,i}) = \delta^h_k(p_{k,i}) \cdot q^h_k, \]

are reduced-form consumer demand functions for meat \( k \) for the United States (U), Canada (C), Mexico (M), and the rest of the world (ROW). Note that market-clearing conditions in the above equations account for trade. In particular, wings, dark meat, and ready-to-eat products are exported to Canada, Mexico, and ROW; however, whole chickens and breast meat are not exported due to high domestic consumption.

**Steady-State Equilibrium**

The impacts of exogenous shocks are analyzed through the changes in the steady-state values of endogenous variables. Under steady state, all dynamic variables are stationary across time (e.g., \( Q_{G,i+2} = Q_{G,i} = Q_{G} \)). Any exogenous shock to the model changes the values of the endogenous variables from the steady state in the baseline to a new steady state under the alternate scenario. Recognizing that equation (56) is a set of five equations, equation (57) represents 15 equations, and \( H^h_k(p_{k,i}) \) contains 15 variables, the above model in its steady-state equilibrium consists of a system of 59 equations (1–55) in 59 endogenous variables (46 quantities: \( S_C, S_{SM}, Q_F, D^F, D^E, Q_E, D^RE, D^RE_F, Q_H, D^H, D^H_E, Q_G, d^G, d^G_L, q_W, q_L, q_P, d^P, d^P_L, Q_{BR}, Q_{Wi}, Q_D, P_P, q_{FP}, d^F_P, d^F_P, q_{RE}, d^F, d^F_L, H^h, S_L \) and 13 endogenous prices: \( P_C, P_{SM}, P_F, P_E, P_H, P_G, P_W, P_{BR}, P_{Wi}, P_D, P_{RE}, P_{FP}, \) and \( P_L \)).

**Data and Calibration**

We use data for quantities and prices for all variables at various stages of the broiler supply chain to calibrate the model. The data for these variables are collected for the 2012–2017 period and averaged to iron out year-to-year fluctuations.\(^\text{12}\) The data for corn and soybeans come from the Feed Grains Database (U.S. Department of Agriculture, 2018b). Since soymeal is used in the chicken feed mix, 1 lb of soybeans is converted to 0.792 lb of soymeal (U.S. Soybean Export Council, 2018). Of the total supply of corn and soymeal for feed, the percentage of corn and soymeal used in the broiler industry in 2016 is obtained from the Animal Food Consumption report (Institute for Feed Education

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\(^{11}\) See Goodwin, McKenzie, and Djumaidi (2003) for a vector autoregressive regression time-series analysis of price relationships among chicken parts in the wholesale broiler market.

\(^{12}\) For some variables, data are not available for the 2012–2017 period; we indicate in the text the years for which the data are available.
& Research, 2017). Of the total feed supply, 4% is used to feed breeder chickens and the remaining 96% is used to feed broiler chickens in grow-out farms. The corn and soymeal prices are collected from U.S. Department of Agriculture (2018f). The feed transfer price is computed as a weighted average of the corn and soymeal prices using the formula 

\[
p_F = (0.58 \times p_C) + (0.42 \times p_{SM}).
\]

The data for the number of fertilized eggs from breeder farms come from the Livestock and Meat Domestic Data (U.S. Department of Agriculture, 2018c), and egg prices for 2016 are from Clauer (2017). The data for the number of DOCs is collected from Quick Stats (U.S. Department of Agriculture, 2018f) and the price of DOCs is obtained from Clauer (2017) for 2016. The number of fully grown chickens is converted into pounds, and the corresponding prices are obtained from Quick Stats (U.S. Department of Agriculture, 2018e). Since transfer-price data for chickens used for further processing are not available, we use chicken-part prices for this transfer price. Data for labor used in grow-out farms, processing plants, and ready-to-eat product production come from the U.S. Bureau of Labor Statistics (2020) and the U.S. Census Bureau (2020).

U.S. consumers have a strong preference for breast meat over dark meat, and exports of breast meat and whole chickens are negligible (U.S. Department of Agriculture, 2018a), implying that domestic consumption is equal to domestic production in these two categories. Data for U.S. exports of dark meat and wings to Mexico, Canada, and ROW is collected from the Foreign Agricultural Service (U.S. Department of Agriculture, 2018d). Domestic consumption for these two meat types is calculated as total production minus exports. Export data for ready-to-eat processed chicken products come from UN Comtrade (2018), and U.S. domestic consumption is computed as production minus exports. The data for ready-to-eat product prices are not available, and we consider this price to be 30% higher than the price of chicken parts.

Canada applies a tariff-rate quota (TRQ) on imports from the United States. Since the TRQ is 0 on imports under 47,000 metric tons (MT) and 249% on imports above this quota (World Trade Organization, 2019), we consider a weighted average tariff of 161%. Mexico does not impose any tariff on dark meat imports from the United States as per the North American Free Trade Agreement (NAFTA) (Hernandez and Hernandez, 2015) and also under the United States–Mexico–Canada Agreement (USMCA). For ROW imports, we use the trade-weighted average tariff rate of 25% (World Trade Organization, 2018). North American transportation costs are $0.095/lb and $0.077/lb for exports to Mexico and Canada, respectively. These transport costs are computed using the volume of a 55,000-lb cargo load of meat per semi truck (World Trade Organization, 2018), cost per truck carriage from Springdale, Arkansas, to Mexico City, Mexico ($5,221.00), and Montreal, Canada ($4,255.00). An additional $240 is included for transportation to Canada to cover the $200 fee for customs paperwork per truck and $400 inspection charges per truck at the U.S.–Canadian border, with 10% of the trucks undergoing re-inspection. The transport cost between the United States and ROW is $0.114/lb. This cost is computed using the ship-cargo weight of 50,000 lb of broiler meat and transport costs of $7,015, $7,110, $5,450, and $5,200 for Hong Kong, South Korea, the Netherlands, and Brazil, respectively. Using these data and the trade-value weighted average, we arrive at $0.114/lb transport cost to ROW.

Using the above data, we calibrate the conversion factors for hatcheries and grow-out farms by taking the ratio of quantity of output to quantity of input, parameters of the CES cost functions and reduced-form supply and demand functions. We consider a low elasticity of substitution.

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13 Personal Correspondence with Nicole Twiford-McKewon, manager bulk commodity pricing, bulk commodity rates and commerce, Tyson Fresh Meats, April 15, 2019.
of 0.2 between feed and DOCs because of the stringent requirement of feed mix and the limited substitutability between feed and DOCs. Following Rutherford (2002), we calibrate share parameters, the returns-to-scale parameters, and productivity parameters. The calibrated parameters are reported in Appendix A. Once the model is calibrated, the baseline simulation is run to verify the model replicates the actual data. The baseline values of key endogenous variables are reported in the first column of Table 2.

### Simulation Analysis

Using the calibrated model, we run three counterfactual scenarios and compare these results to baseline values to assess the impacts of the COVID-19 pandemic on the broiler supply chain. The first scenario examines the effects of a labor reduction due to COVID-19-induced illness of workers. The second scenario investigates the impacts of the decrease in U.S. consumers’ income due to unemployment resulting from COVID-19. The third scenario analyzes the combined effects of the first two scenarios. Before presenting the results, we validate the model by comparing the simulation results of price to actual data.

### Model Validation

To check the validity of the model performance, we compare simulation results of key prices from scenario 3 of the combined labor and income reduction shocks against average data over the period February through September. Table 1 presents these comparisons. Given the month-to-month volatility amid the pandemic, for comparison to the simulation results, we calculate an average price change recorded in the data as follows. For a given price, we calculate the percent change for each month for February through September relative to January 2020. We then average the price changes over February through September to obtain the average price change. For the feed inputs and feed market, the simulation results closely mimics the average real price data. For example, the model predicts the corn and soymeal prices fall by 12.87% and 0.78%, respectively, and the price data show a drop of 14.21% and 0.77%, respectively. The feed price in the simulation declines by 7.38% and the feed price data for the broiler industry fell by an average of 6.03% during the pandemic. For the retail markets, the simulation results indicate that the whole chicken, breast meat, and dark meat prices rise by 6.51%, 5.43%, and 6.25% and the data show a price increase of 11.80%, 4.70%, and 7.70%. The model predicts that the weighted average (of whole chicken, breast meat, dark meat, and wing) prices increase by 5.44% compared to 5.87% in the data.

In summary, comparison of the simulation results for prices to the actual data demonstrates that the model performs reasonably well and that the model can be used for counterfactual analysis.

### Simulation Results

In spite of the U.S. government’s effort to keep the processing plants operating, many workers were unable to work because of the high infection rate, creating labor shortages in the broiler supply chain. Consequently, many processing plants across the country temporarily closed their operations or operated at a lower capacity due to maintenance of COVID-19-related safety measures at work sites (Hauser, 2020; Wiener-Bronner, 2020). Therefore, for the first scenario, we consider a 35% reduction in the workforce in the production plants. As a result, production interruptions reverberated

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14 Studies have also analyzed other exogenous shocks on the broiler market. For example, Thomsen and McKenzie (2001) examined the impacts of food recalls and the resulting government supports on publicly traded meat and poultry firms.

15 Note that labor shocks during the initial COVID-19 outbreak was severe and lasted for only a couple months at the height of the pandemic, but the second and third wave can prolong the labor shock unless measures are taken to safeguard the worksite environment. By contrast, the income shocks will likely last for an extended period. Therefore, the labor shock scenario is only for the current period, whereas the income shock will last beyond 2020.
Table 1. Comparison of Price Changes from Simulation Results and Actual Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scenario Three</th>
<th>Dataa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn price</td>
<td>−12.87%</td>
<td>−14.21%</td>
</tr>
<tr>
<td>Soymeal price</td>
<td>−0.78%</td>
<td>−0.77%</td>
</tr>
<tr>
<td>Feed price</td>
<td>−7.38%</td>
<td>−6.03%</td>
</tr>
<tr>
<td>Whole chicken price</td>
<td>6.51%</td>
<td>11.80%</td>
</tr>
<tr>
<td>Breast meat price</td>
<td>5.43%</td>
<td>4.70%</td>
</tr>
<tr>
<td>Dark meat price</td>
<td>6.25%</td>
<td>7.70%</td>
</tr>
<tr>
<td>Weighted average retail price</td>
<td>5.44%</td>
<td>5.87%</td>
</tr>
</tbody>
</table>

Notes: a Average increase in price from February to September relative to January.
Data for corn price, soymeal price, and feed price are from ERS Livestock & Meat Domestic Data (U.S. Department of Agriculture, 2018c). Data for whole chicken price, breast meat price, and dark meat price are from ERS Meat Price Spreads. Data for weighted average retail price (broiler price index) are from BEA Price Indexes for Personal Consumption Expenditures by Type of Product.

through the entire broiler supply chain. The results of this scenario for price, supply, retail demand, and export quantity changes are reported in the second column in Table 2.

A 35% reduction in employment shifts the labor supply to the left. These labor shortages cause two effects: higher wage rate and reduced production capacity. Both of these effects drastically curtail the production in processing plants, causing a production decline in whole chickens (5.36%), chicken parts (9.23%), and dressed chickens for further processing (8.06%). Since the outbreak of COVID-19, the popular press has frequently reported shortages of chicken meat (Bomey and Tyko, 2020; Gellerman, 2020). The results show that prices increase for whole chickens (13.28%), breast meat (11.1%), wings (13.92%), dark meat (12.83%), and dressed chickens for further processing (14.1%) because of the supply reduction of these chicken products.

Since workers in the processing of ready-to-eat chicken products also suffered from COVID-19, labor shortages also occurred at this stage of the production process. This labor shortfalls, coupled with the supply reduction of chickens for further processing, drastically reduced the supply of ready-to-eat chicken (14.08%), resulting in a larger price increase (22.91%) relative to the price of unprocessed products.

With the sudden and unexpected labor contraction, processing plants could not use all of the live birds from grow-out farms. As fewer chickens were slaughtered, demand for live chickens in the upstream grow-out farms dramatically plummeted, and consequently, these chickens were stranded from further movement through the supply chain. With mounting feed costs and fast-growing broilers, the unexpected over-supply of grown chickens resulted in grow-out farmers euthanizing broilers to control costs. The rippling effects of the culling of live chickens were felt in the upstream segments as demand for DOCs, fertilized eggs, and feed also declined, causing the prices in these segments to also fall.

With the contraction of the chicken-meat supply, the quantity of various meats sold domestically and in export markets fell sharply. In particular, U.S. consumers consumed less whole chickens (5.36%) and breast meat (9.23%). U.S. exports of all meat types also declined; however, U.S. exports of dark meat to other countries fell much less than the corresponding domestic sales. This indicates that health-conscious consumers in the United States decreased dark meat consumption more than consumers in other countries. U.S. consumers also significantly reduced their consumption of ready-to-eat chicken meat because of the significant decline in supply of this meat category and closure of restaurants.

Table 3 presents welfare changes arising from the labor shortages in the broiler supply chain. The producer surplus in the upstream segments (corn, soymeal, feed, fertilized eggs, and grown chickens) is negative because of lower demand for these products in the downstream segments,
Table 2. Impacts of COVID-19 Shocks on Prices, Supply, Consumption, and Exports

<table>
<thead>
<tr>
<th>Price</th>
<th>Baseline(^a)</th>
<th>Labor (% change)</th>
<th>Income (% change)</th>
<th>Labor &amp; Income (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn ($/tonne)</td>
<td>166.14</td>
<td>−3.03</td>
<td>−10.08</td>
<td>−12.87</td>
</tr>
<tr>
<td>Soymeal ($/tonne)</td>
<td>420.44</td>
<td>−0.17</td>
<td>−0.60</td>
<td>−0.78</td>
</tr>
<tr>
<td>Feed ($/tonne)</td>
<td>266.22</td>
<td>−1.73</td>
<td>−5.77</td>
<td>−7.38</td>
</tr>
<tr>
<td>Fertilized eggs ($/dozen)</td>
<td>3.36</td>
<td>−1.26</td>
<td>−6.30</td>
<td>−7.46</td>
</tr>
<tr>
<td>DOCs ($/dozen head)</td>
<td>4.32</td>
<td>−1.25</td>
<td>−6.26</td>
<td>−7.42</td>
</tr>
<tr>
<td>Grown chicken ($/lb)</td>
<td>0.55</td>
<td>−1.34</td>
<td>−5.83</td>
<td>−7.07</td>
</tr>
<tr>
<td>Whole chicken ($/lb)</td>
<td>1.48</td>
<td>13.28</td>
<td>−6.12</td>
<td>6.50</td>
</tr>
<tr>
<td>Breast meat ($/lb)</td>
<td>3.34</td>
<td>11.10</td>
<td>−5.15</td>
<td>5.43</td>
</tr>
<tr>
<td>Wings ($/lb)</td>
<td>1.72</td>
<td>13.92</td>
<td>−6.34</td>
<td>6.77</td>
</tr>
<tr>
<td>Dark meat ($/lb)</td>
<td>1.56</td>
<td>12.83</td>
<td>−5.88</td>
<td>6.25</td>
</tr>
<tr>
<td>Processed chicken ($/lb)</td>
<td>2.30</td>
<td>14.10</td>
<td>−6.15</td>
<td>7.19</td>
</tr>
<tr>
<td>Ready-to-eat product ($/lb)</td>
<td>2.99</td>
<td>22.91</td>
<td>−5.26</td>
<td>16.50</td>
</tr>
<tr>
<td>Weighted average retail ($/lb)</td>
<td>2.76</td>
<td>11.11</td>
<td>−5.15</td>
<td>5.44</td>
</tr>
<tr>
<td>Wage rate ($/hr)</td>
<td>13.88</td>
<td>73.69</td>
<td>−3.45</td>
<td>67.75</td>
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</table>

<table>
<thead>
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<th>Supply</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Corn (thousand tonnes)</td>
<td>0.04</td>
<td>−0.06</td>
<td>−0.22</td>
<td>−0.28</td>
</tr>
<tr>
<td>Soymeal (thousand tonnes)</td>
<td>0.01</td>
<td>−0.33</td>
<td>−1.12</td>
<td>−1.46</td>
</tr>
<tr>
<td>Feed (thousand tonnes)</td>
<td>0.09</td>
<td>−0.10</td>
<td>−0.33</td>
<td>−0.43</td>
</tr>
<tr>
<td>Fertilized eggs (million dozens)</td>
<td>1.09</td>
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<td>−0.26</td>
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<tr>
<td>DOCs (million dozens)</td>
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<td>−0.29</td>
<td>−0.45</td>
</tr>
<tr>
<td>Grown chicken (million lb)</td>
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<td>−0.16</td>
<td>−0.29</td>
<td>−0.45</td>
</tr>
<tr>
<td>Whole chicken (million lb)</td>
<td>4.10</td>
<td>−5.36</td>
<td>−2.31</td>
<td>−7.61</td>
</tr>
<tr>
<td>Breast meat (million lb)</td>
<td>6.07</td>
<td>−9.23</td>
<td>−0.26</td>
<td>−9.51</td>
</tr>
<tr>
<td>Dark meat (million lb)</td>
<td>7.06</td>
<td>−9.23</td>
<td>−0.26</td>
<td>−9.51</td>
</tr>
<tr>
<td>Wings (million lb)</td>
<td>1.78</td>
<td>−9.23</td>
<td>−0.26</td>
<td>−9.51</td>
</tr>
<tr>
<td>Processed chicken (million lb)</td>
<td>18.26</td>
<td>−8.06</td>
<td>−0.72</td>
<td>−8.76</td>
</tr>
<tr>
<td>Ready-to-eat (million lb)</td>
<td>18.51</td>
<td>−14.08</td>
<td>−1.15</td>
<td>−15.09</td>
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</table>

<table>
<thead>
<tr>
<th>U.S. consumption of</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole chicken (million lb)</td>
<td>4.10</td>
<td>−5.36</td>
<td>−2.31</td>
<td>−7.61</td>
</tr>
<tr>
<td>Breast meat (million lb)</td>
<td>6.07</td>
<td>−9.23</td>
<td>−0.26</td>
<td>−9.51</td>
</tr>
<tr>
<td>Wings (million lb)</td>
<td>1.59</td>
<td>−9.24</td>
<td>−0.26</td>
<td>−9.52</td>
</tr>
<tr>
<td>Dark meat (million lb)</td>
<td>0.90</td>
<td>−14.78</td>
<td>2.94</td>
<td>−12.34</td>
</tr>
<tr>
<td>Ready-to-eat (million lb)</td>
<td>18.26</td>
<td>−9.25</td>
<td>−0.46</td>
<td>−9.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. exports to Canada</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wings (million lb)</td>
<td>0.02</td>
<td>−4.60</td>
<td>−2.73</td>
<td>−7.22</td>
</tr>
<tr>
<td>Dark Meat (million lb)</td>
<td>0.28</td>
<td>−7.45</td>
<td>−1.25</td>
<td>−8.62</td>
</tr>
<tr>
<td>Ready-to-Eat (million lb)</td>
<td>0.03</td>
<td>−4.64</td>
<td>−2.81</td>
<td>−7.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. exports to Mexico</th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Wings (million lb)</td>
<td>0.02</td>
<td>−6.81</td>
<td>−1.59</td>
<td>−8.30</td>
</tr>
<tr>
<td>Dark meat (million lb)</td>
<td>1.27</td>
<td>−6.30</td>
<td>−1.86</td>
<td>−8.05</td>
</tr>
<tr>
<td>Ready-to-eat (million lb)</td>
<td>0.08</td>
<td>−6.94</td>
<td>−1.66</td>
<td>−8.53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>U.S. exports to ROW</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wings (million lb)</td>
<td>0.16</td>
<td>−9.81</td>
<td>0.03</td>
<td>−9.80</td>
</tr>
<tr>
<td>Dark meat (million lb)</td>
<td>4.60</td>
<td>−9.07</td>
<td>−0.38</td>
<td>−9.42</td>
</tr>
<tr>
<td>Ready-to-mat (million lb)</td>
<td>0.14</td>
<td>−10.06</td>
<td>−0.05</td>
<td>−10.15</td>
</tr>
</tbody>
</table>

Notes: * Units in parentheses in the first column are for baseline values.
where the impacts of the labor shortfalls are severe. With declining prices and lower quantities of production, producers in these segments experience losses. The feed segment incurs the largest loss, $392 million, followed by the corn segment with a loss of $191 million. Since feed is a major input in the broiler supply chain, feed producers experience large negative impacts when production in the supply chain falters. The hatchery segment is not impacted significantly because of limited employment of hired labor. The producer surplus in the downstream segments (whole chickens, chicken parts, chickens for further processing) increases because the effects of the rise in retail prices outweigh the decrease in quantity due to labor shortages. The further processing segment benefits the most, with a producer surplus gain of $961 million. The ready-to-eat chicken segment in the downstream sector incurs losses because of a large reduction in quantity used due to the closure of fast-food restaurants and dine-in services. The overall net producer welfare in the entire vertical link is $−218 million, indicating the severity of the labor shock due to COVID-19 infections.

Turning to consumer surplus, all retail chicken segments in all countries incur welfare losses. In the United States, the ready-to-eat chicken segment experiences the largest decline ($12.1 billion) because restaurants shut down. The next segment with large loss is breast meat, with $−2.2 billion in losses because demand, which is the leading category of U.S. chicken consumption, declined considerably. Consumer surplus also falls in Canada, Mexico, and ROW, with the breast meat segment experiencing the largest decline. The overall decline in consumer surplus in all retail chicken-meat segments is $−17.5 billion.

Next, we discuss the simulation results of the second scenario. The COVID-19 pandemic caused the worst-ever recession in the second quarter of 2020 (Horsley, 2020). In spite of a one-time supplemental income and unemployment insurance payments by the U.S. government, low-income households did not have adequate income to buy all the needed groceries, such as meat products (Parker, Horowitz, and Brown, 2020). We examine the effects of this income reduction by lowering expenditures on purchase of chicken meat by 5% and analyze the ensuing effects seeping through the broiler supply chain.

The economic recession and falling food expenditures caused demand to contract, shifting the demand functions for various chicken-meat products to the left. The actual quantity of consumption of these products is determined by substitution among chicken products due to relative price changes. U.S. whole chicken, breast meat, and wing consumption fall, causing prices to decline. U.S. exports of chicken products to all three foreign destinations fall (except wing exports to ROW), which is another reason for the lower prices. By contrast, demand for U.S. dark meat increases by 2.94% because dark meat, with a price decline of 5.88%, is relatively cheaper. Though U.S. consumption of dark meat increases, the decline in exports of dark meat to all countries causes total sales of dark meat to fall modestly, by 0.26%. These demand changes permeate the upstream segments. Consistent with the demand patterns, the quantity of all chicken products fall. As the production decreases in various stages of the supply chain, labor employment falls and the wage rate decreases by 3.45%, which is in contrast to the wage increase in Scenario 1 due to labor supply contraction. Because of the decline in quantities of chicken parts, the quantity of grown chickens decreases by 0.29%, with a corresponding price decline of 5.83%. Further upstream, demand for DOCs, fertilized eggs, and feed falls, as do their respective prices.

Because prices and quantities fall due to reduced demand in this scenario, the producer surplus in the entire vertical link (except for the ready-to-eat segment) declines. The largest loss occurs in further processing ($−1.5 billion), followed by the feed segment ($−1.3 billion), and chicken parts ($−971 million). By contrast, the ready-to-eat chicken segment experiences a small gain in producer surplus because of the cheaper processed chicken input. Overall, the net decline in producer surplus in the entire broiler supply chain is $4.8 billion, which is considerably more than the fall in producer surplus in the labor-shock scenario.

Consumers in all countries generally benefit in this scenario because the decline in price is more pronounced than the decline in quantity of consumption. Consumers of breast meat, particularly in the United States, gain the most. The net gain in consumer surplus across all countries is $5 billion.
Table 3. Impacts of COVID-19 Shocks on Producer and Consumer Surplus ($ millions)

<table>
<thead>
<tr>
<th></th>
<th>Reduction in Labor</th>
<th>Reduction in Income</th>
<th>Reduction in Labor &amp; Income</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Producer surplus</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>−190.83</td>
<td>−606.66</td>
<td>−782.43</td>
</tr>
<tr>
<td>Soymeal</td>
<td>−10.60</td>
<td>−34.78</td>
<td>−45.84</td>
</tr>
<tr>
<td>Feed</td>
<td>−392.13</td>
<td>−1,251.10</td>
<td>−1,616.24</td>
</tr>
<tr>
<td>Fertilized eggs</td>
<td>−67.86</td>
<td>−321.27</td>
<td>−382.19</td>
</tr>
<tr>
<td>DOCs</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Grown chicken</td>
<td>−25.72</td>
<td>−98.79</td>
<td>−122.66</td>
</tr>
<tr>
<td>Whole chicken</td>
<td>49.33</td>
<td>−143.37</td>
<td>−98.20</td>
</tr>
<tr>
<td>Chicken parts</td>
<td>69.97</td>
<td>−970.83</td>
<td>−908.14</td>
</tr>
<tr>
<td>Processed chicken</td>
<td>961.27</td>
<td>−1,464.48</td>
<td>−557.22</td>
</tr>
<tr>
<td>Ready-to-eat product</td>
<td>−611.61</td>
<td>64.33</td>
<td>−532.20</td>
</tr>
<tr>
<td><strong>Net producer surplus</strong></td>
<td>−218.19</td>
<td>−4,826.94</td>
<td>−5,044.77</td>
</tr>
</tbody>
</table>

| **Consumer surplus**   |                    |                     |                            |
| **U.S.**               |                    |                     |                            |
| Whole chicken          | −823.87            | 359.63              | −446.76                    |
| Breast meat            | −2,234.09          | 1,039.83            | −1,196.23                  |
| Wings                  | −378.66            | 172.94              | −201.56                    |
| Dark meat              | −172.06            | 83.87               | −92.28                     |
| Ready-to-eat           | −12,102.56         | 2,837.26            | −9,128.99                  |
| **Canada**             |                    |                     |                            |
| Wings                  | −6.40              | 0.35                | −6.04                      |
| Dark meat              | −118.19            | 15.99               | −101.76                    |
| Ready-to-eat           | −32.99             | −0.41               | −33.50                     |
| **Mexico**             |                    |                     |                            |
| Wings                  | −3.76              | 1.62                | −2.05                      |
| Dark meat              | −263.40            | 112.49              | −145.04                    |
| Ready-to-eat           | −52.49             | 11.62               | −39.79                     |
| **ROW**                |                    |                     |                            |
| Wings                  | −47.60             | 17.43               | −29.87                     |
| Dark meat              | −1,156.24          | 410.53              | −738.01                    |
| Ready-to-eat           | −114.30            | 21.01               | −92.62                     |
| **Net consumer surplus**| −17,506.60         | 5,084.15            | −12,254.51                 |

The third scenario combines the supply-side shock of labor reduction and demand-side shock of expenditure decline to analyze the joint effects on the broiler supply chain. Since the effects of this scenario are the cumulative effects of the first two scenarios, the COVID-19-induced impacts on the broiler supply chain are generally more pronounced. Results in the fourth column of Table 2 clearly underscore the severity of adverse negative effects from the COVID-19 pandemic as production processes in all segments are hit hard, causing retail prices to increase because of the production decline. Quantity changes at various stages of the supply chain of the two scenarios reinforce each other, leading to larger negative cumulative effects. The declines in retail quantities in this combined scenario range from 7.61% for whole chickens to 15.09% for ready-to-eat products.
The increase in retail prices is not as steep as in Scenario 1 because the negative price effects of Scenario 2 mitigate the price-increasing effects of Scenario 1. For example, price increases for whole chickens, chicken parts, and ready-to-eat products in Scenario 1 are dampened by price declines in Scenario 2, resulting in smaller positive combined effects. Scenario 1 increases the prices of meat products due to reduced production arising from labor shortage. However, Scenario 2 decreases the price of meat products due to demand reduction arising from lower expenditure. The rises in retail prices range from 5.43% for breast meat to 16.5% for ready-to-eat products. The average price increase of all meat products is about 5.44%, which is comparable to the 5.87% aggregate chicken product price increase reported by the Bureau of Economic Analysis. Because processors do not want to transfer grown chickens from grow-out farms to processing plants due to lack of labor, 0.45% of grown chicken are euthanized. The upstream segments also experience the negative impacts, leading to reduced demand for inputs (DOCs, fertilized eggs, and feed). Consequently, prices of these inputs plummet. These input-price declines are more pronounced because the changes in Scenarios 1 and 2 reinforce each other.

The wage rate in this scenario increases because of the labor shortages, arising from workers’ illness, outweigh the lower labor use in production, arising from reduced sales of chicken products. The pronounced increase in the wage rate (67.75%) highlights the severity of the COVID-19-induced infections and labor shortages in processing plants. In the upstream part of the supply chain, since both prices and quantities fall, large revenue declines occur. But in the retail segments, prices increase but quantities decrease more, resulting in revenue declines. Finally, the declines in exports of chicken products of Scenarios 1 and 2 reinforce each other, leading to larger negative effects.

Since this scenario combines the labor shock in Scenario 1 and income shock in Scenario 2, the welfare measures in this scenario largely reflect the sum of the welfare changes in the first two scenarios. The producer surplus in all segments (except DOCs) is negative—even in the downstream segments—because the large decline in producer surplus due to income reduction outweighs the rise in producer surplus of labor shocks. The feed segment incurs the largest producer surplus loss (−$1.6 billion), followed by the chicken parts segment (−$908 million). The total decline in producer welfare is −$5 billion. The consumer surplus in this scenario is negative in every retail chicken market because the larger decline from the labor reduction shock dominates the gain form the income reduction shock. In the United States, the ready-to-eat chicken segment experiences the largest fall in consumer surplus (−$9.1 billion), followed by the breast meat segment (−$1.2 billion).

The overall welfare decline (i.e., the sum of producer surplus and consumer surplus losses) in the broiler sector as a result of the COVID-19 catastrophe amounts to −$17.3 billion.

Sensitivity Analysis

We conduct several sensitivity analyses to check the robustness of the model’s performance and to simulate different labor and income shocks as the pandemic enters its third wave. The sensitivity analyses for labor shock reflect the severity of labor shortages as workers become infected with COVID-19, the second and third surge of coronavirus spread, and policy measures taken to safeguard worker safety by avoiding crowded work environments through social distancing. To examine various degrees of potential social distancing policies and because the exact labor shock in the broiler industry is unknown, we consider 0%–50% reductions in labor employment, which covers the 35% used in the main analysis. The 0% reduction covers the baseline scenario before COVID-19, and a 50% reduction reflects the severe case of extensive COVID-19 infections among workers without the executive order deeming the workers to be essential. A modest reduction of 25% could reflect a proper implementation of safeguard policies such as social distancing.
Figure 1. Sensitivity Analysis for Various COVID-19-Induced Labor Shocks

Figure 1 presents the results of these sensitivity analyses for key variables (price and quantity of fully grown grow-out chicken and breast meat). As expected, the graph shows that changes in prices and quantity are lower for labor shocks smaller than the 35% in the main analysis and higher for shocks above the main analysis. For example, for a small labor shock of about 4%, the price and quantity of fully grown broilers fall by 0.13% and 0.01%, respectively. However, for the case of a 50% reduction, the price and quantity of fully grown broilers decrease by 2.31% and 0.29%, respectively. In the retail market, for the 4% and 50% labor shocks, the price of breast meat increases from 1.05% to 19.90%, while the quantity of breast meat falls by 0.95% and 15.38%. Figure 1 depicts that, over the range of labor shocks, the price and quantity changes for fully grown broiler and breast meat move roughly linearly.

Second, because the exact reduction in consumer expenditures on retail broiler products is unknown, we implement a range of income shocks from a 1% to a 10% reduction in chicken expenditures, which covers the 5% reduction in the main analysis. Figure 2 depicts the results of these sensitivity analyses for price and quantity of fully grown chickens and breast meat. The 1% reduction in expenditures causes fully grown broilers and breast meat prices to decline by 1.31% and 1.15%, respectively. The reduction in quantities is minimal, at about 0.06% for both fully grown broilers and breast meat. A similar trend (large price reduction relative to quantity reduction) holds as the income shock expands. For example, for the largest income shock, prices for grown chicken and breast meat fall by 11.54% and 10.28%, respectively, while the quantity reductions for these two products are about 0.60%. These large price changes and small quantity changes are because of a rightward shift in supply (due to decline in input prices upstream) and leftward shift in demand (due to income decline), which has an amplifying impact on price but an offsetting impact on quantity. As

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16 In the interest of space, we present the sensitivity results only for these key variables. The other variables exhibit similar trends.
## Conclusions

Because of crowded working environment, widespread COVID-19 outbreaks occurred among meat-processing workers; these outbreaks were further exacerbated by President Trump’s executive order to keep meatpacking plants open. As a result, by the end of July 2020, 43,750 workers in 530 meatpacking and food-processing plants became seriously ill with COVID-19 (Nittle, 2020), causing many processing plants in various states to shut down and leading to a significant decline in chicken processing. These adverse effects reverberated through both upstream and downstream segments of the broiler supply chain. In the upstream segments, grow-out chicken farmers were not able to move the fully grown chickens to processing plants due to a lack of adequate labor. Consequently, millions of chickens had to be humanely depopulated, causing severe economic losses. Further, grow-out chicken farmers were not demanding DOCs from hatcheries, which did not want to buy fertilized eggs, resulting in lower demand for feed. In the downstream segments, because meat-processing plants were hot spots for COVID-19 infections, many plants were temporarily closed or operating at less than full capacity. This resulted in reduced production of chicken products for retail markets and caused meat shortages at grocery stores. On the demand side, the fall in income and food expenditure due to job losses and closure of restaurants curtailed overall demand for food products. However, in the meat sector, the demand decline from restaurant closures was mitigated by increased purchases for home cooking.

In this study, we analyze the effects of these two channels on the entire broiler supply chain. We model the various stages of the broiler supply chain, which allows us to examine the effects of the COVID-19 pandemic throughout the broiler supply chain in detail. The results show that the labor

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<table>
<thead>
<tr>
<th>Price of Grow-out Broilers</th>
<th>Price of Breast Meat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in Income</td>
<td>Reduction in Income</td>
</tr>
<tr>
<td>% Change in Price</td>
<td>% Change in Price</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity of Grow-out Broilers</th>
<th>Quantity of Breast Meat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in Income</td>
<td>Reduction in Income</td>
</tr>
<tr>
<td>% Change in Quantity</td>
<td>% Change in Quantity</td>
</tr>
<tr>
<td>−0.6</td>
<td>−0.6</td>
</tr>
<tr>
<td>−0.4</td>
<td>−0.4</td>
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<tr>
<td>−0.2</td>
<td>−0.2</td>
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<tr>
<td>0.0</td>
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</tbody>
</table>

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Figure 2. Sensitivity Analysis for Various COVID-19-Induced Income Shocks

with the labor shock, the price and quantity results for fully grown broilers and breast meat roughly increase linearly over the range of income shocks.
shocks have adverse negative effects on quantities produced throughout the supply chain, causing meat shortages and higher prices for chicken products at retail stores. However, the reduced demand for grown chickens lowered the prices in the upstream sectors. The demand-side shocks lower both quantities and prices at various stages of the supply chain (except for dark meat). The labor-shortage shocks adversely impact the broiler supply chain more than the expenditure-reduction shocks.

Since the third scenario implements Scenarios 1 and 2 simultaneously, the combined effects are generally more pronounced as the effects of each scenario reinforce each other. However, the prices in the retail markets have opposite effects, with labor shocks and meat shortages generating positive price effects and income shocks and reduced meat demand causing negative price effects; the resulting net effect is that retail prices increase.

The results of our study have important policy implications. Because our study quantifies the negative impacts of COVID-19 on prices and quantities, the results are useful for producers and consumers at various stages of the supply chain, state and federal policy makers, and agribusiness firms such as feed producers and exporters. Agents in the various segments of the supply chain can take precautionary measures to mitigate the catastrophic shocks of future pandemics. Meat-processing plants are hot spots for coronavirus infections, causing worker illness, labor shortages, and reduced meat production. Even though these workers are deemed essential, when they are severely ill, they could not come to work. Given the extensive disruptions and economic losses in the broiler supply chain due to workers’ illness, it is important to control the spread of COVID-19 and safeguard the health of these workers from future infections arising from a new wave of the coronavirus. Our findings underscore the importance of controlling the rapid spread of coronavirus in meat-processing units through mask wearing, maintaining social distance, paid sick leave to incentivize exposed or infected workers to quarantine, contract tracing, and designating workers to specific groups, limiting clustering of workers, and extending hours of operation at processing plants to avoid overcrowding. Since chicken products are essential meat items for consumers, controlling coronavirus infection at the work site and keeping processing plants operating will lead to a steady supply of chicken meat. The U.S. government has implemented food-box programs to feed poor and unemployed families. Extending this program until the COVID-19 pandemic is controlled and workers are back on the job would help both consumers and chicken-meat producers.

[First submitted August 2020; accepted for publication January 2021.]
References


### Appendix A

#### Table A1. Calibrated Parameters

<table>
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<tr>
<th>Description</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Scale parameter, corn supply</td>
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<td>Return to scale, chicken parts</td>
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<td>Share parameter, chicken parts: broilers</td>
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<td>Share parameter, ready-to-eat: further processing</td>
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