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Disasters, population trends, and their impact on the U.S. pork packing sector☆

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ABSTRACT

In 2020, disruptions and risks from COVID-19 led to meatpacking plant shutdowns and reductions in total slaughter relative to 2019. Debate emerged surrounding the vulnerability of the packing industry and whether larger plants were more prone to reductions in slaughter compared to smaller plants. Using a novel panel dataset of 40 major U.S. hog slaughter plants, we estimate packers' propensities to reduce production relative to their normal operational capacity, controlling for plant characteristics, local labor conditions, and severe weather events. We find larger plants are, on average, more likely to reduce daily slaughter and that an increase in plant physical capacity leads to an increase in the quantity reduced. However, we do not find a statistically significant relationship between plant capacity and shutdowns. We find strong evidence that factors indirectly limiting labor availability—the average number of COVID-19 cases, the location of plants in population-loss areas, and the presence of a severe weather event—increase slaughter reductions. These findings suggest physical capacity is not the only factor influencing processing rates and highlight existing vulnerabilities to labor shortages.

1. Introduction

The 2019 fire at the Tyson meatpacking plant in Holcomb, Kansas and the increasing COVID-19 infections among employees at slaughter plants from early-April to mid-June 2020 sparked interest in examining the meat industry's resiliency to shocks (Hayes et al., 2021; US-HAC, 2021). There is concern that the concentration of meat packing—defined here as a few plants dominating the industry—could leave national production vulnerable to disruptions that can negatively impact producers along the entire supply chain (Ma and Lusk, 2021).

In response to concerns about concentration and competition in the meat sector, the Federal government has proposed programs to assist the processing industry, often with a focus on small- and medium-sized packing plants. For example, in July 2021, the U.S. Department of Agriculture (USDA) announced a plan to invest $500 million to support expansion of processing capacity and an additional $150 million for existing small and very small processing plants (USDA, 2021a). Similarly, in January 2022, the Biden-Harris administration announced a plan to dedicate $1 billion in American Rescue Plan funds to the expansion of independent processing capacity (The White House, 2022). On November 2, 2022, USDA announced $223 million in grants and loans in a first round of investment aimed at increasing competition and expanding meat and poultry processing capacity (USDA, 2022a). However, changes to the number, size, and design of slaughter facilities may not benefit all participants in the meat marketplace. The size of slaughter facilities contributes to economies of scale that translate into lower meat prices for consumers under normal conditions (Hobbs, 2021).

In this article, we characterize the relationship between pork packing plants' *individual* characteristics and their ability to withstand shocks. Using a correlated random effects (CRE) double hurdle model with panel data we investigate the likelihood of a plant reducing daily slaughter (participation decision) and the volume by which they reduced slaughter during the first year of the COVID-19 pandemic (quantity decision). Then, we examine the subset of plants that reduced slaughter to zero (temporarily shut down) and the factors that influenced the

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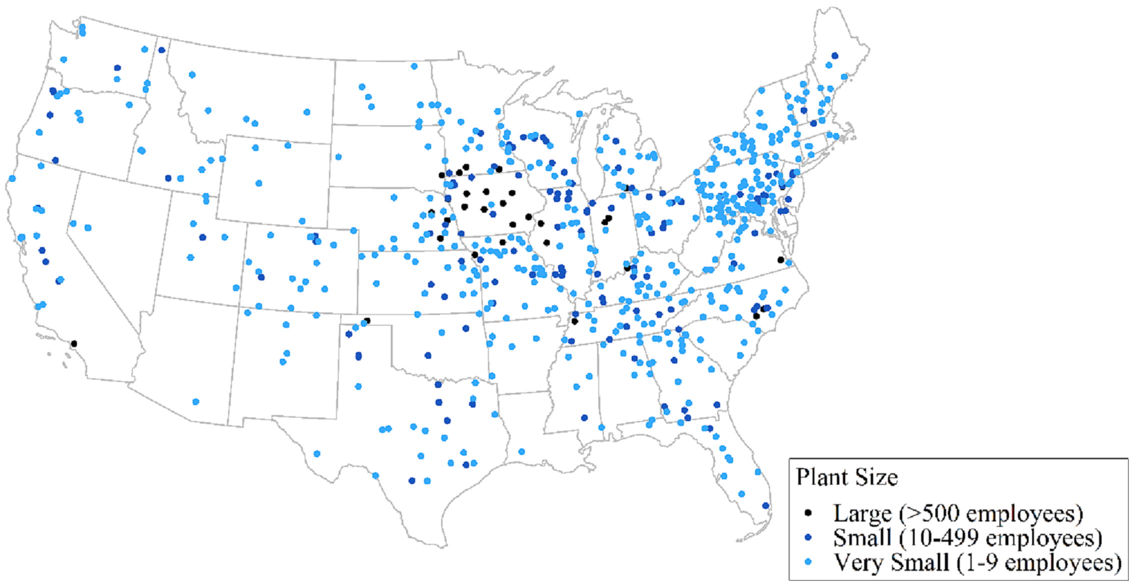

Fig. 1. Location and size of federally inspected pork packing plants in the United States. Source: USDA-Food Safety and Inspection Service's (FSIS) Meat, Poultry and Egg Product Inspection (MPI) Directory: https://www.fsis.usda.gov/inspection/establishments/meat-poultry-and-egg-product-inspection-directory. Note: Plant size refers to the size of the establishment based on the business class. Large plants have 500 employees or more, small plants have between 10 and 499 employees, and very small plants have fewer than10 employees. This map omits plants in Alaska, Hawaii, Puerto Rico, and other U.S. territories.

likelihood of a shutdown. This work addresses the question of whether plant physical capacity (our measure of plant size), environmental disasters (e.g., severe snowstorm, fire, hurricane), and local labor and county characteristics affect pork packers' processing decisions.

The resilience of larger plants features prominently in discussions around government interventions in meatpacking. Medium- and small-sized plants have been perceived as more resilient to shocks (e.g., the COVID-19 pandemic) than larger facilities because of their increased production during the pandemic (Huffstutter and Nickel, 2020; Rude, 2021; Thilmany et al., 2021), however, no empirical study uses plant-level slaughter data to evaluate the effect of plant characteristics on the likelihood that a processing facility reduces processing or shuts down. Studies related to meatpacking focus on analyzing the sector using aggregate state and regional weekly slaughter data (Bina et al., 2022; Padilla et al., 2021; Vaiknoras et al., 2022). To the best of our knowledge, this article is the first to use plant-level data to evaluate the factors influencing processing decisions. To conduct this analysis, we use a novel, restricted use, panel dataset of daily slaughter volumes of the 40 largest federally inspected (FI) hog slaughter plants spanning April 2020 through March 2021 (USDA-AMS, 2021). Using panel data in this context, we can control for individual unobserved heterogeneity and model some of the processing dynamics over time.

Throughout the 2020–2021 study period, the incidence of reduced daily processing exceeded plant closures. Our results indicate plant physical capacity positively impacted the likelihood of reducing daily slaughter volumes and increases in physical capacity resulted in greater reductions to daily slaughter volumes. We do not find a statistically significant relationship between plant capacity and shutdowns. Together, these results suggest that while larger plants were vulnerable to factors that disrupted slaughter, they were able to reduce slaughter strategically in lieu of closing down, especially later in the pandemic. In addition, physical capacity is not the only constraint in processing—factors that limit labor availability and, therefore, operational capacity also play an important role in the study of plant processing decisions. Thus, our findings suggest that environmental disasters, increases in COVID-19 cases, and consistent population loss—all of which indirectly impact labor availability—affect reductions in processing.

The rest of this paper is organized as follows. Section 2 provides background on the pork processing industry in the United States and describes how the COVID-19 pandemic disrupted this industry in 2020–2021. Section 3 describes the data used to assess the impacts of plant and county characteristics, and natural disasters on slaughter reductions and shutdowns during the first year of the COVID-19 pandemic. Section 4 explains our modeling approach, followed by the results in Section 5. Section 6 discusses the implications of our results for U.S. policies related to labor, meat supply chain investments, and climate adaptation. Finally, Section 7 concludes with suggestions for future research.

2. The pork processing industry: structure and the COVID-19 pandemic

The structure of the meatpacking industry has changed profoundly over the last 50 years—processing centers shifted from urban to rural locations as the average plant size grew. Before the mid-1950s, most meatpacking plants were near stockyards in urban areas. By the 1980s, plants with fewer than 50 employees in urban locations began to close and larger plants with over 1,000 workers opened in rural areas (Broadway and Ward, 1990). This consolidation also facilitated the adoption of cost-cutting strategies such as locating plants near animal feeding operations to reduce transportation costs. The race for scale economies was a key driver of consolidation (MacDonald and Ollinger, 2000). By 1997, plants that slaughtered over a million hogs annually accounted for 87% of hog slaughter, while the same size plants accounted for just 38% of slaughter in 1977 (MacDonald et al. 2000). Research suggests the four-firm concentration ratio for pork-packing plants has slowed over the past five years with the entry of smaller packing plants. The concentration level has fallen to the industry's concentration ratio observed in the mid-2000s (Cook et al., 2022).

In 2021, a few large plants dominated hog slaughter: 33 out of the 645 FI plants (approximately 5%) slaughtered 92% of the FI hogs in the United States (USDA-NASS, 2022). Simultaneously, over 95% of facilities (430 plants) slaughtered fewer than 1,000 hogs a year each and together accounted for only 0.1% of total FI slaughter (USDA-NASS, 2022). Hog slaughter facilities are geographically clustered, tending to

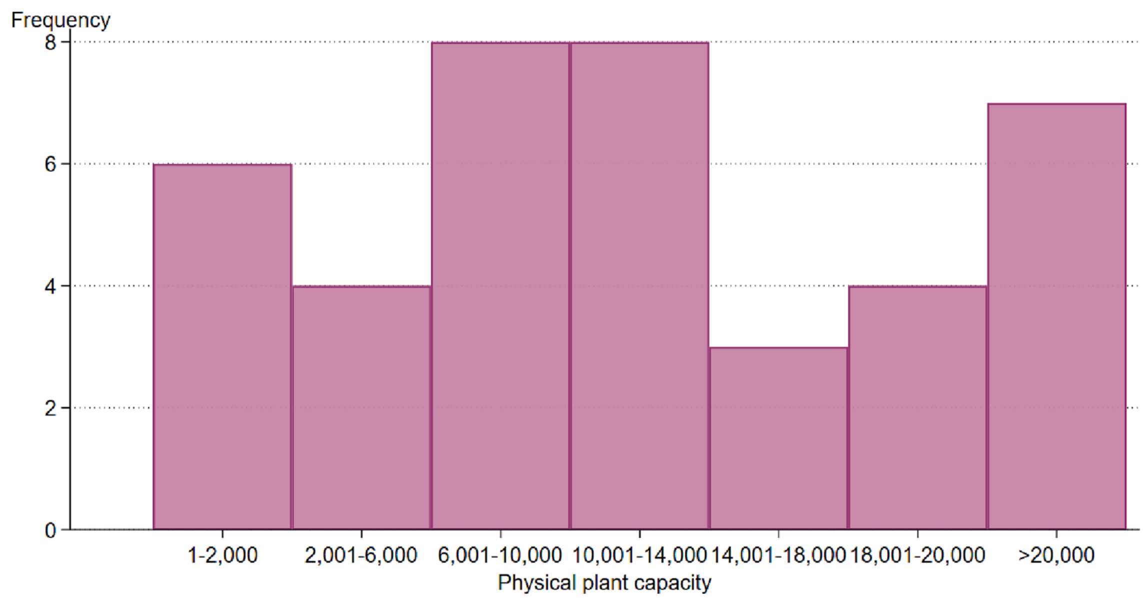

Fig. 2. Histogram of plant physical capacity. Source: USDA-AMS data on plant-level, daily slaughter volumes.

be located close to hog production. As Fig. 1 shows, many of the major FI plants are in the Midwest (USDA-FSIS, 2021).[1] The states with the most large-capacity plants include North Carolina, Missouri, Illinois, Iowa, Minnesota, and Indiana.

2.1. Pork packing plants in the COVID-19 pandemic

At the start of the COVID-19 pandemic, meatpacking plants across the United States struggled to continue operations largely due to worker illness and absence. The disruptions and risks from COVID-19 led to plant shutdowns and reductions in total slaughter relative to 2019 (Hayes et al., 2021; Padilla et al., 2021; Tonsor and Schulz, 2020; Vaiknoras et al., 2022). For example, one of the world's largest processing facilities in North Carolina, which can slaughter up to 35,000 hogs per day, closed for several days near the beginning of the pandemic (Barnes, 2020). The largest year-over-year reduction in weekly slaughter occurred the week ending May 2, 2020, when total hog slaughter fell 35% below the 2019 level for that same week (Lusk et al., 2021).

Low wages and benefits can in part explain the difficulties surrounding employment in the meatpacking sector during COVID-19. Luckstead et al. (2022) find that current wages in meatpacking were not high enough for workers to take on exposure risk from COVID-19 and that benefits (retirement, signing bonus, and health insurance) lead to higher willingness to accept a meatpacking job. Other potential factors include the labor conditions at slaughter plants, which tend to increase workers' likelihood of contracting COVID-19 (CDC, 2021b; Dyal et al., 2020). These characteristics include close contact (within 6 feet) with other workers for more than 15 min, cold temperatures in the facility, and shared transportation and housing among workers. As of May 31, 2020, there were 16,233 confirmed cases of and 86 deaths from COVID-19 among workers from 239 meat processing plants in 23 states (Waltenburg et al., 2020).

Reductions in capacity, including temporary shutdowns, of any of these large plants affects total pork supply, as smaller plants cannot absorb the additional volume of hogs (Lusk, 2020). When a packing plant closes, there is excess supply of livestock relative to packers' processing abilities. During the first months of the COVID-19 pandemic, hog producers were unable to sell expected quantities of finished hogs to packing plants and received a lower price, reducing producer revenue (Lusk et al., 2021; Vaiknoras et al., 2022).

3. Data and summary statistics

In this article, we apply a correlated random effects (CRE) double hurdle model to panel data to investigate whether plant physical capacity (our measure of plant size), environmental disasters (e.g., severe snowstorm, fire, hurricane), and local labor and county characteristics affect pork packers' processing capabilities. We use data from USDA Agricultural Marketing Service (AMS), the Centers for Disease Control and Prevention (CDC), the Bureau of Labor Statistics (BLS), the Federal Emergency Management Agency (FEMA), and the U.S. Census Bureau to conduct our empirical analysis. The following sections describe the pork plants in our data, how we define a local area surrounding a pork plant, and county and state-level demographic data.

3.1. Panel on daily slaughter volumes

Our primary dataset is a panel of daily slaughter volumes for 40 major FI hog slaughter plants in the United States (USDA-AMS, 2021). The dataset, compiled by USDA-AMS, contains variables indicating current daily slaughter, operational capacity normally employed, physical plant capacity, plant location, and whether a plant closed or reduced slaughter volume relative to their operational capacity on a given day from the beginning of April 2020 to the end of March 2021. Physical capacity is the maximum productive capability, measured as number of hogs that can be slaughtered in a day. Fig. 2 displays the distribution of size across plants in the dataset. Over half of the plants in the dataset have a physical capacity between 1 and 14,000 hogs per day.

Operational capacity in this context indicates how much of the total physical capacity a facility normally employs in the absence of production shocks. Reduced slaughter volume is the difference between operational capacity and current daily slaughter. To maintain

[1] All pork produced for retail sale and most pork sold across state lines must come from hogs slaughtered and processed under continuous federal inspection (FI). Inspection includes examination and checking or testing of a carcass or pork against established government standards. Pork from hogs slaughtered and processed under state inspection only—non-federal inspection (NFI)—is limited to intrastate commerce with few exceptions (USAD-NASS, 2022). In this article, we focus on FI plants as they account for approximately 90% of production.

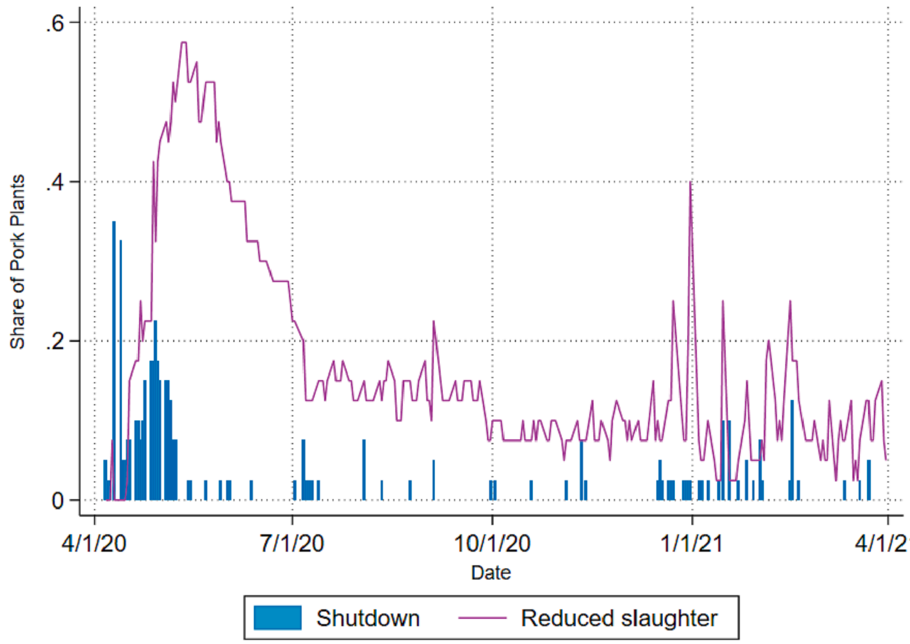

Fig. 3. Daily share of federally inspected pork plants that reduced slaughter relative to their operational capacity or temporarily shutdown, April 2020 to April 2021. Source: USDA-AMS data on plant-level, daily slaughter volumes.

confidentiality of the plants included in this panel, we withhold information related to location of the plants in the summary statistics, but we use this information for estimation.

The 40 plants in this dataset harvest barrows and gilts, process over 700 hogs per day, and account for approximately 90% of U.S. FI hog slaughter. We merge the panel data with static, plant-specific characteristics such as age of the plant, ownership structure (LexisNexis, 2021), and distance from the plant to the closest metro area.[2]

During the study period, plants appear to have responded to challenges from the pandemic by reducing daily slaughter volumes more often than shutting plants down with most of the temporary closures concentrated in the first three months of the pandemic (Fig. 3). In May 2020, 57% of plants in the sample reduced slaughter relative to their operational capacity, a high in the study period. The share of plants closing was also high at the onset of the pandemic, with 35% of plants in the sample temporarily shutting down in early April 2020.

On average, the distance from a plant to the closest metro area is around 43 miles, consistent with plants being primarily located outside an urban setting (Table 1). Approximately 13% of plants are located in an area that has experienced population loss for the last 5 years.

The structure of this panel dataset has several advantages over aggregate national or regional slaughter data. The detail of these data facilitates the examination of daily changes in slaughter and plant closures while controlling for other plant, county, and area characteristics. The data only includes medium and large sized plants (over 700 hogs slaughtered daily), which limits our ability to evaluate how COVID-19 affected small plants. To the best of our knowledge, no dataset exists that tracks plant-level, daily slaughter rates for small pork plants. Because of this data limitation, we are unable to examine how pork plants that slaughtered fewer than 700 hogs daily reacted to the COVID-19 pandemic. However, the plants in our dataset account for 90% of hogs slaughtered in the United States. It would be worthwhile to study the resilience and production decisions of small plants, but ultimately their performance has a minor effect on the overall resilience of the U.S. pork packing sector.

Although daily slaughter data is not available for small plants, we do know the location of federally inspected small and very small plants.[3] We use these data to examine whether proximity to smaller plants could have affected the performance of nearby larger plants in the dataset. On average, there are about two small pork plants within a 25 mile radius from the location of plants in the sample (Table 1).

Lastly, the dataset includes daily slaughter volumes on a five-day-week production schedule (Monday–Friday), excluding Saturday slaughter. Packers use Saturday slaughter to accommodate increased slaughter during peak weeks without hiring new employees and to make up for lost slaughter during holiday weeks (Mitchel, 2016). While this data limitation prevents evaluating responses in Saturday slaughter during the first year of the pandemic, it does not hinder our ability to determine how plant and local area characteristics affected daily shutdown and plant slaughter reduction decisions for business-week schedules. For example, at the onset of the pandemic, COVID-19 prevalence similarly affected pork processing plants through worker constraints during the week and on Saturdays. Missing Saturday slaughter could potentially attenuate our results for other key explanatory variables. If an environmental disaster, such as a severe snowstorm, extended into the weekend and disrupted operations, the effect of the presence of a disaster on the probability of reducing slaughter would be larger.

3.2. CDC COVID-19 restricted case surveillance data

We merge the daily slaughter dataset with CDC's restricted data on county-level daily COVID-19 reported cases, as the prevalence of COVID-19 in the community may influence daily slaughter capacity through workforce availability (CDC, 2021a). The CDC COVID-19 case

[2] We define a metro area as a city or town that has a population of at least 50,000 people. We use ArcGIS to determine the distance from city center to the exact location of the plant.

[3] We rely on the USDA-Food Safety and Inspection Service's (FSIS) Meat, Poultry and Egg Product Inspection (MPI) Directory's listing and classification of plants by size. Plant size refers to the size of the establishment based on the business class. Small plants have between 10 and 499 employees and very small plants have 10 employees or fewer.

Table 1
Summary statistics of federally inspected pork packing plants, local areas, and counties in data sample (April 2020 through March 2021).

	Mean	St. Dev.	Min	Max
Daily hogs slaughtered in 2020–2021	10,847	7,405	–	–
Plant capacity (maximum number of hogs slaughtered in a day) *	11,842	7,725	–	–
Reduced slaughter quantity (difference between operational capacity and current daily slaughter) *	871	2,692	0	–
Estimated number of employees*	1,689	1,050	60	4,500
Age of the plant (years)*	40	23.60	–	–
Percent of shutdown days	1.9	0.14	0	100
Percent of days with reduced volume	16	0.37	0	100
Distance (mi.) from plant to metro area (2020) *	42.70	30.14	0	112.20
Percent of plants that are part of a corporation*	87.5	0.33	0	100
Number of unemployed people in area (25-mile radius surrounding plant) *	49,965	145,284	435	1,138,641
COVID-19 cases in the county (7-day moving average) *	117.47	889.96	0	19,105
Percent of days with a severe weather incident in area (25-mile radius surrounding plant) *	1.41	0.12	0	100
Number of very small and small pork plants in area (25-mile radius surrounding plant) *	2.35	2.41	0	8
Percent of days with a stay-at-home order*	11.8	0.32	0	100
Percent of plants located in population-loss areas*	12.5	0.34	0	100
Number of plants	40			

Notes: Variables with an asterisk (*) are included in the estimation of eq. (1)–(3). Maximum and minimum values are excluded for some of the plant-level variables to protect the confidentiality of the data. Percent of shutdown days refers to the sum of closed days across plants divided by the number of plants multiplied by the days in the sample. Percent of days with reduced volume refers to the sum of days with slaughter volume less than the operational baseline across plants divided by the number of plants multiplied by the days in the sample. Similarly, percent of days with a severe weather incident in the area refers to the sum over the number of days with a severe weather event across plants in the sample divided by the number of days multiplied by the number of plants. A corporation refers to a legal business structure that is separate and distinct from its owners (e.g., Limited Liability Company (LLC), S-Corporation, or C-Corporation). Other plants in the sample are either a sole proprietorship or a partnership.

data comes from counties voluntarily sharing the daily number of positive tests. However, the data omits dates with no reported cases. Given this structure, we assume there are zero COVID-19 cases in a county if the county reported no positive test results to the CDC, and we recode the missing values for weekdays.[4] While helpful in gauging transmission rates in a county, the CDC COVID-19 dataset suffers from two limitations. First, the data undercounts the incidence of COVID-19 due to underdiagnoses and underreporting. Second, there are generally lags in reporting cases to the CDC (Galaitsi et al., 2021). To mitigate the latter, we use the seven-day moving average of COVID-19 cases. COVID-19 cases in counties in the dataset sharply increase in the winter months (Fig. 4), consistent with trends observed across the United States.

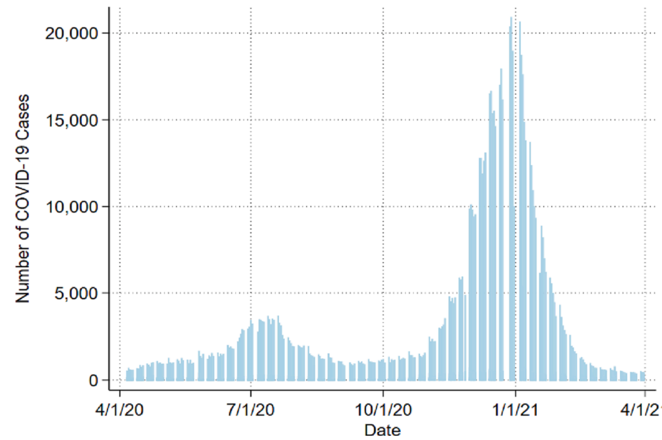

Fig. 4. Daily COVID-19 cases in counties with large pork packing plants. Source: CDC COVID-19 Case Surveillance Restricted Access Detailed Data (CDC, 2021a).

3.3. BLS local area unemployment statistics

The BLS Local Area Unemployment Statistics database provides monthly, county-level labor statistics such as the size of the labor force, number of unemployed people, and the unemployment rate (US-BLS, 2021). In this article, we use the number of unemployed persons (actively looking for work but not yet employed) in the “local area” of a plant as a measure of labor availability (Table 1). We develop local areas for each plant in our sample to account for plants drawing workers from neighboring counties. A local area includes all counties whose borders are within a 25-mile radius from the location of a plant. Using this characterization, in lieu of only including counties that border a county with a plant, adds necessary flexibility to our model. For example, if a county with a pork plant is small and surrounding counties are also small, it is probable for workers to travel two or three counties over to get to the plant. Similarly, if the county with the plant is large, the availability of labor in surrounding counties might be less important. As a robustness check, we consider alternative definitions of a local area and estimation results (using counties whose borders are within a 10-, 20-, 30-, 40-, or 50-mile radius from the location of a plant) are available in Appendix B.

3.4. Federal Emergency Management Agency (FEMA) disaster data

We use FEMA disaster declaration summary data to create a binary, daily variable indicating whether a federally declared disaster occurred in counties within a 25-mile radius of a plant’s location. We omit FEMA declarations of COVID-19 but include all other disasters (e.g., severe ice storms, hurricanes, fires, and snowstorms). In the study period, there were 142 days (1.4% of the data) across 12 different pork plants with a federally declared disaster (Table 1).

3.5. County and state demographics

We use county population data from the U.S. Census Bureau to create a local area population loss indicator variable (U.S. Census Bureau, 2021). For each plant in the sample, we define a population-loss area as one that has consecutively lost population for the last five years (Table 1). An indicator variable on whether the area surrounding a packing plant has experienced population loss gives information on the

[4] This assumption may not hold for weekend days as many locations across the United States reported fewer cases on the sixth and seventh day of the week (Galaitsi et al., 2021). However, our panel of hog slaughter plants does not include Saturday and Sunday slaughter.

trends of resident growth.

Lastly, we include the start and end of each state's stay-at-home orders.[5] For most of the states in the sample, these orders lasted from May 2020 to August 2020. It is unclear if these orders directly affected plant shutdown decisions as Executive Order 13917 defined meat-packing plants as essential infrastructure.[6]

4. Empirical approach

We apply the double-hurdle model proposed by Cragg (1971) to reflect the two decisions in reducing daily slaughter relative to operational capacity. The first hurdle estimates the probability that plant *i* in county/local area *j* in state *h* will operate at a reduced production schedule (participation decision) on day *t*. The second hurdle captures the degree of reduction (quantity decision)—the difference between normal operational capacity and daily slaughter rate. We estimate a Mundlak-Chamberlain device correlated random effects (CRE) double hurdle model (Chamberlain, 1984; Mundlak, 1978):

$$r_{it} = \alpha_1 + \beta_1 \boldsymbol{W}_i + \delta_1 \boldsymbol{X}_{jt} + \gamma_1 \boldsymbol{P}_{ht} + c_i + \phi_1 \boldsymbol{m} + \theta_1 (s_i \times \boldsymbol{m}) + \omega_1 (s_i \times d_{jt}) + \epsilon_{ijt} \tag{1}$$

$$q^*_{it} = \alpha_2 + \beta_2 \boldsymbol{W}_i + \delta_2 \boldsymbol{X}_{jt} + \gamma_2 \boldsymbol{P}_{ht} + c_i + \phi_2 \boldsymbol{m} + \theta_2 (s_i \times \boldsymbol{m}) + \omega_2 (s_i \times d_{jt}) + \nu_{ijt} \tag{2}$$

$$q_{it} = r_{it} q^*_{it} \tag{3}$$

where the r_{it} is a binary variable equal to 1 if the plant reduced processing on a given day t; and, q^*_{it} is the latent variable representing the quantity reduced (computed as the difference between operational capacity and current daily slaughter). We only observe $q^*_{it} > 0$ when $r_{it} = 1$, in which case the observed quantity reduced $q_{it} = q^*_{it}$. Otherwise, $q_{it} = 0$. In this model, there is no threshold for reduction; we include any deviation between operational capacity normally employed and daily slaughter as a reduction.

$\boldsymbol{W}_i$ is a vector of plant-level variables that includes physical plant capacity (s_i), log of age of the plant, distance to the closest metro area in miles, and a binary variable indicating if a plant is part of a corporation. The age of a plant can proxy for the level of automation, potential maintenance and downtime required, the ability to run a plant at maximum capacity, and other unobserved characteristics. Similarly, if a plant is part of a corporation, greater resources to mitigate worker absences or the spread of COVID-19 in the plant (higher wages, protective equipment) might be available.

$\boldsymbol{X}_{jt}$ is a vector of local area and county variables. Specifically, the log of monthly unemployed persons in the area, presence of a disaster, an indicator for population loss area, the number of small and very small pork plants in the area, and the seven-day moving average of COVID-19 cases in a county. Consistent population loss over the last five years can be indicative of adverse conditions in an area; and, with a shrinking population, a plant might experience difficulty hiring new employees.

$\boldsymbol{P}_{ht}$ includes state-level stay-at-home orders and state controls while c_i captures the unobserved, time-invariant, plant-level heterogeneity. With the CRE approach, we allow for correlation between the time-constant unobserved heterogeneity, c_i, and the explanatory variables (Wooldridge, 2019). More specifically, c_i is a function of the plant-level time averages of the observed explanatory variables (Chamberlain, 1984; Mundlak, 1978), which we control for by including the time averages as additional regressors in the estimating equation (Wooldridge, 2010; Wooldridge, 2019; Gautam and Ahmed, 2019). With the CRE specification, we can include time-constant plant characteristics and obtain estimates for these variables while controlling for unobserved heterogeneity (Wooldridge, 2019).[7]

We include a vector of monthly indicator variables $\boldsymbol{m}$ and two interactions terms. First, we interact plant physical capacity s_i with $\boldsymbol{m}$ to capture the effect of plant size over time. Second, we interact the disaster variable d_{jt} with plant physical capacity to gauge any effect plant size might have on reductions when a disaster is in place. Lastly, both ϵ_{ijt} and ν_{ijt} are the error terms for equations (1) and (2), respectively.

Following Burke (2009), Verkaart et al. (2017), and Adusah-Poku and Takeuchi (2019), we estimate the first hurdle using a CRE probit and report the average partial effects (APEs) for each regressor b_{ijt}, which represents the derivative of the probability of reducing production, $\partial P[r_{it} > 0 | W, X, P]/\partial b_{ijt}$. We estimate the second hurdle using a truncated normal regression model and we estimate the partial effects of each regressor by taking the derivative of the expected value of q_{it} conditional on participating: $\partial E[q_{it} W, X, P, r_{it} > 0]/\partial x_{ijt}$. Lastly, the unconditional expected value $E[q_{it}|W, X, P]$ is the overall effect that can be decomposed into the conditional expectation and the probability of a positive value for r_{it}. We follow Adusah-Poku and Takeuchi (2019) and report these three APEs in the results section. Appendix A contains coefficient estimates from each regression.

4.1. Modeling temporary shutdowns

Plant-level and local labor characteristics may affect the likelihood of a temporary shutdown (complete reduction in processing) differently than they do a partial reduction. For example, the onset of COVID-19 disrupted plants to the point of closure, but shutdowns virtually stopped as COVID-19 cases continued to increase in 2021. However, partial reductions in processing were prevalent throughout the study period. We would then expect COVID-19 cases to have a statistically significant effect on the probability of reducing production but not completely shutting down. To this end, we estimate the following CRE probit model, where the outcome of interest y_{it} is a binary variable indicating whether plant i closed on day t:

$$\Pr\left(y_{it} \middle| \boldsymbol{W}_i, \boldsymbol{X}_{jt}, \boldsymbol{P}_{ht}, \boldsymbol{m}\right) = \lambda + \theta \boldsymbol{W}_i + \mu \boldsymbol{X}_{jt} + \chi \boldsymbol{P}_{ht} + c_i + \tau m + \theta_1 (s_i\ x\ m) + \omega_1 (s_i\ x\ d_{jt}) + u_{ijt} \tag{4}$$

This specification uses the same vectors of variables and interactions as equations (1) and (2). We report the APEs in the results section of this paper and the coefficients for the estimation using a local area of 25 miles in Appendix A.

5. Results

5.1. Double hurdle model estimation results

Table 2 reports three different APEs from the correlated random effects (CRE) double hurdle model examining slaughter reductions. Column (1) reports APEs from the first hurdle (the probability of reducing slaughter, r_{it}) and columns (2) and (3) are the APEs of the conditional (second hurdle) and unconditional expectations (joint) of quantity reduction, q_{it}, respectively.

[5] We find little variation between state- and county-level stay-at-home orders. Only one county had stay-at-home orders that differed from the state-level order.

[6] Under this order, the president's powers under the Defense Production Act (DPA) are delegated to the Secretary of Agriculture to determine priorities and the allocation of materials and services. The executive order sought to ensure the continued supply of meat while maintaining compliance with CDC and OSHA guidance for livestock processing plants issued on April 26, 2020 (Duer, 2020). As Fig. 2 shows, plant shutdowns continued to occur after then-President Trump signed the order.

[7] CRE differs from the fixed effects (FE) estimation in that a CRE specification includes time averages in the regression, as opposed to removing the time averages (FE approach). See Wooldridge (2019) for a complete discussion of these methods.

Table 2
Estimated APEs for the double hurdle model.

	(1) Probability of reduction $P[r_{it} > 0 \mid W, X, P]$	(2) Conditional mean of quantity reduced $E[q_{it} \mid W, X, P, r_{it} > 0]$	(3) Unconditional mean of quantity reduced $E[q_{it} \mid W, X, P]$
Plant characteristics			
Plant physical capacity (1,000 hogs processed/day)	0.0099***(0.003)	197.0***	78.5***
	(0.003)	(4.69)	(17.7)
Age (log)	0.062*	814.7**	409.1**
	(0.036)	(324.5)	(161.7)
Corporation	−0.185**	1,519	−490.4
	(0.089)	(1,293)	(451.1)
Distance to the closest metro area (10 miles)	0.0294***	609.0***	236.3***
	(0.011)	(193.4)	(59.81)
Area characteristics			
Disaster	0.118*	4,217***	1,768***
	(0.065)	(1,432)	(570.6)
Number of unemployed persons (log) in area	0.0075	2,344	466.9
	(0.079)	(2,077)	(561.9)
Population-loss area indicator	0.073	1,951***	666.1*
	(0.087)	(253.3)	(382.8)
Number of small pork plants in area	0.002	−224.9	–33.57
	(0.017)	(149.5)	(81.58)
County and state characteristics			
Average COVID-19 cases in county (1,000 cases)	0.006***	145.8	50.83**
	(0.002)	(105.2)	(24.73)
Stay-at-home order	−0.074*	1,369**	−55.41
	(0.041)	(623.1)	(226.4)
Observations	9,789	1,806	9,789

Notes: Clustered-standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We omit some of the not statistically significant variables and the state and monthly controls. See Appendix A for the coefficient table.

We find plant physical capacity and distance to the closest metro area have a statistically significant and positive effect on the probability of reducing slaughter rate and the quantity reduced (Table 2). For each additional 1,000 hogs per day of physical slaughter capacity, a plant would be close to one percentage point more likely, on average, to reduce slaughter. The APEs of plant physical capacity on quantity reduced in columns (2) and (3) demonstrate that increases in plant physical capacity marginally increases the difference between operational capacity and daily slaughter (q_{it}). As expected, plant physical size is not the only determinant of slaughter. A 10-mile increase in the distance to the closest metro area would result in almost a 3-percentage point increase in the probability of reducing slaughter and a 600-unit decrease in quantity. Being located farther away from a metro area could impact labor availability as well as resources available to urban, metro areas (i.e., public transportation, snow plowing services). Both partial effects are relatively small in magnitude but suggest that conditions which may impact labor tend to be statistically important. The APEs of log age of the plant on the probability of reducing slaughter and the overall effect on observed quantity reduced were both positive and statistically significant. A 10% increase in plant age is associated with a 0.62 percentage point increase in the probability of reducing slaughter, indicating older plants might be more susceptible to disruptions. The statistical significance of this variable is not always consistent across estimations using alternative definitions of local area (Appendix B).[8]

Plants that are part of a corporation are 18.5 percentage points less likely to reduce daily slaughter. This effect suggests that plants with potentially more resources are less likely to reduce slaughter. For example, plants that are part of a corporation could have benefited from additional information about the spread of COVID-19, and/or resources to fight its spread such as personal protective equipment and early access to vaccinations. It is also possible that corporations could have strategically shifted labor and/or pigs between plants to avoid slaughter reductions. As described by MacDonald (2003), packers "that own multiple plants can direct livestock flows among them in such a way as to keep plant labor and capital fully employed at a planned level of hours of use" (p. 431). Pudenz and Schulz (2023) describe this as multi-coordination and show how beef packers have comprehensively implemented this business practice since 2005.

Two area-level variables have a statistically significant effect on the quantity reduced. First, the presence of a disaster positively affects both the likelihood of reducing and the quantity reduced. The probability that a plant decreases slaughter increases by 11 percentage points when a federally declared disaster occurs. Similarly, conditional on reducing, the presence of a disaster results in an expected decrease in slaughter of over 4,000 hogs per day. On average, plants in the sample slaughtered 10,847 hogs per day during the study period (Table 1) and a reduction of 4,000 hogs represents close to 40% of average daily slaughter. These results are the first to quantify the effect of a disaster on hog processing, demonstrating the detrimental result of these events on quantities slaughtered. This APE is statistically significant when using alternative definitions of local area, but the magnitude varies between 2,369 and 4,800 hogs per day (Appendix B).

We examine the interaction between plant size and the occurrence of a disaster to determine the vulnerability of larger plants to disasters. Fig. 5 shows a very weak increase in the APE of disaster on the unconditional expectation of reduced quantity at higher plant physical capacity levels. When an area experiences a disaster, it can be more difficult for a plant to operate efficiently. For example, plant workers might struggle to reach the plant under a severe snowstorm. Similarly, the delivery of the hogs from the farm to the processing plant might also be difficult. The very weak increase suggests production disruptions resulting from a disaster are marginally larger among plants with higher physical capacity. For plants with a processing capacity of fewer than 7,000 hogs per day, the APE of disaster on quantity reduced is not statistically different from zero at the 5% level. Although the effect is statistically significant for larger plants, the confidence intervals are wide in part due to the small percentage of days with a disaster.

[8] Appendix B includes APEs estimated using alternative definitions of a local area and a discussion of how APEs of interest are largely consistent across different local area sizes, both in terms of sign and magnitude, although the statistical significance can vary. We consider counties within a 10-mile, 20-mile, 30-mile, 40-mile, and 50-mile area surrounding a pork plant in the sample.

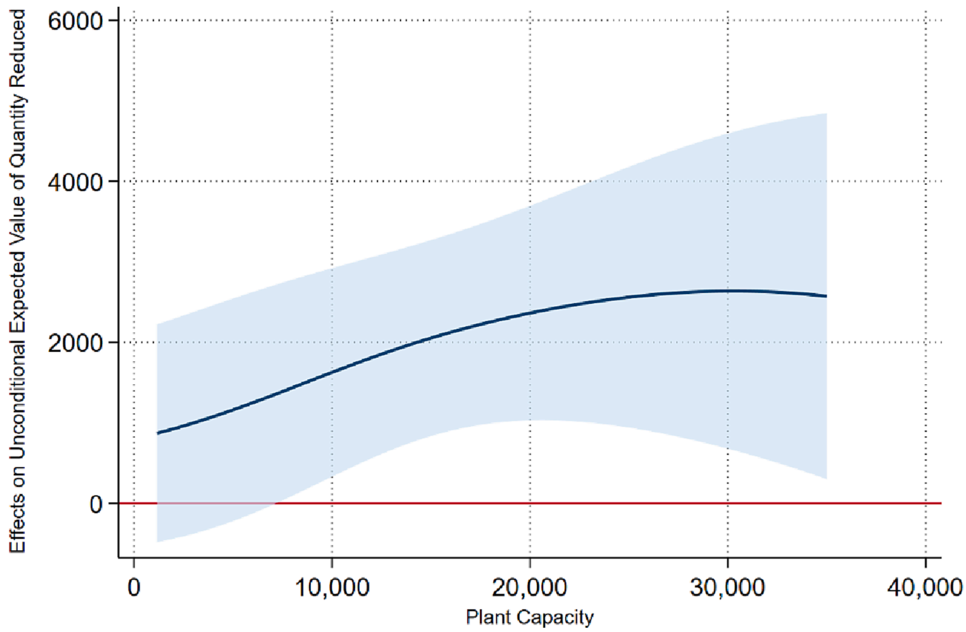

Fig. 5. Average partial effect of the presence of a disaster on quantity reduced evaluated over the support of plant capacity.

Second, plants located in a "population-loss" area were not more likely to reduce slaughter; however, conditional on reducing slaughter, plants in population-loss areas reduced slaughter by over 1,900 hogs per day (17% of average daily slaughter) on average. Consistent, recent declines in population could be indicative of declining economic and social conditions in an area. The thin local labor market could, in turn, influence a packing plant's ability to find qualified labor, leaving the plant more susceptible to decreases in processing relative to the operational baseline. The magnitude of the APE is large relative to other variables, such as plant capacity and distance to the closest metro area. This effect is robust in estimations using a local area definition that includes counties within 10 and 20 miles from the plant's location. When considering larger radiuses as the local area (counties within 40 and 50 miles from the plant), the sign of the APE changes. When the local area is larger, fewer plants (5% of the sample) are in a population loss area and although the effect is statistically significant there is almost no variation in the variable.

Lastly, stay-at-home policies had a negative and statistically significant effect on the likelihood of reducing daily slaughter while reported cases of COVID-19 has a positive but small effect. On average, plants were 7 percentage points less likely to reduce production when state stay-at-home orders were in place. We can attribute this decrease in probability to reduced spread of COVID-19 when orders were in place, which translates into a larger available workforce. Although we also control for COVID-19 cases, the stay-at-home orders could have a more immediate effect than is picked up by official case counts, which likely lag the onset of illness. In addition, this effect could be capturing the sharp decline in the share of pork plants that reduced slaughter from May 2020 to July 2020 (Fig. 3), which coincided with stay-at-home orders.

5.2. Effects on the probability of plant shutdown

The second model of interest is a CRE probit model in which the binary dependent variable measures whether a plant temporarily shut down. We do not find a statistically significant relationship between plant physical capacity and the probability of a shutdown occurring during the entire study period (Table 3). This lack of an effect is in part explained by very few plant closures after the onset of the pandemic, in which plants implemented policies to reduce transmission of COVID-19, such as increased testing, the use of personal protective equipment, and installing physical barriers between workers (Padilla et al., 2021; Waltenburg et al., 2020).

Table 3
Average partial effects (dependent variable: plant shutdowns).

Variables	CRE probit
Plant characteristics	
Plant physical capacity (1,000 hogs processed/day)	0.00015
	(0.0008)
Age (log)	−0.007*
	(0.004)
Corporation	−0.0007
	(0.009)
Distance to the closest metro area (10 miles)	0.005**
	(0.002)
Area characteristics	
Disaster	0.128**
	(0.059)
Number of unemployed persons (log) in area	0.028
	(0.018)
Population-loss area indicator	0.0176**
	(0.007)
Number of small pork plants in the area	−0.0008
	(0.003)
County and state characteristics	
Average COVID-19 cases in county (1,000 cases)	−9.29e-05
	(0.001)
Stay-at-home order	0.006
	(0.008)
Observations	9,036

Notes: Clustered-standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We omit some of the not statistically significant variables and the state and monthly controls. See Appendix A for the table of coefficients.

Similar to the results from the first hurdle, the presence of a disaster, being located farther from a metro area, and being in a population-loss area increase the probability of a plant shutdown. More specifically, the presence of a federally declared disaster is associated with a 13-percentage-point increase in the probability of shutting down.

While being in a population-loss area does not affect the probability of a slaughter reduction, a plant located in an area with consistent population decline is, on average, 1.8 percentage points more likely to temporarily close, indicating the importance of population growth to the

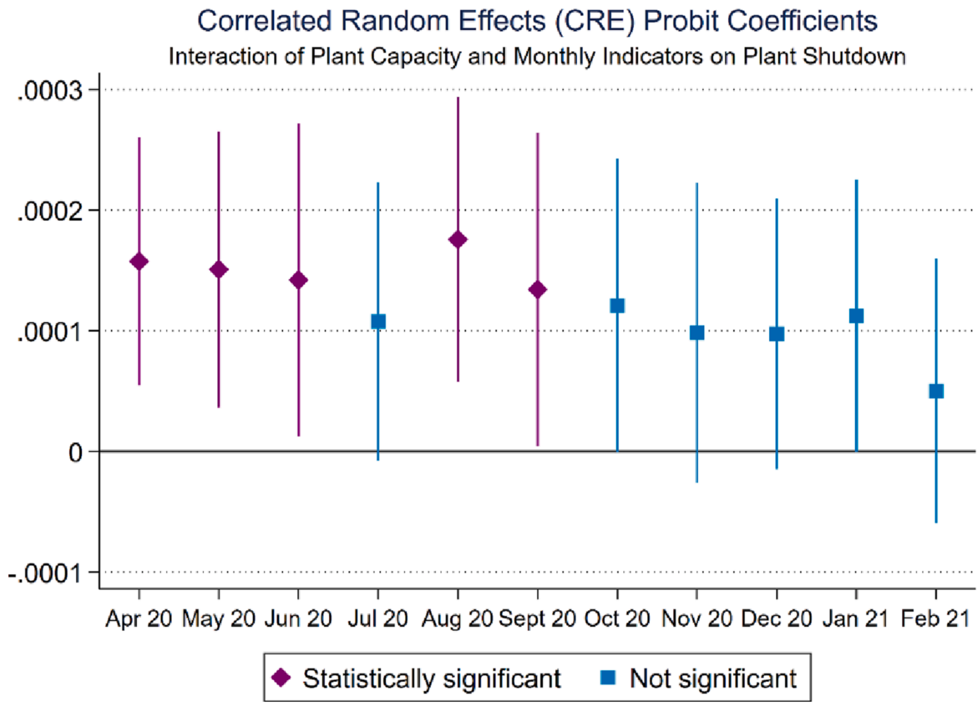

Fig. 6. Coefficients of the interaction of plant capacity with time. Notes: These APEs are relative to the reference category of March 2021, the last month in the dataset. The figure displays 90% confidence intervals.

continuity of operations of larger pork packing plants. Being located an additional 10 miles from a metro area makes a plant 0.49 percentage points more likely to temporarily close. Labor availability is an important factor determining daily slaughter (Bina et al., 2022) and factors that potentially limit labor supply can hinder plants to the point of closure, especially in times when worker absences are high. Although these three factors have the potential to indirectly impact labor availability, the effects of being in a population loss area and distance from a metro on the probability of shutting down are much smaller than that of a disaster. This difference can be in part explained by the various ways in which a disaster can impact plant operations. The presence of a disaster not only disrupts the ability of workers getting to the plant, but the supply of hogs from the farm and the supply of pork to retail markets.

5.3. Was plant capacity more important at the onset of the COVID-19 pandemic?

While we do not find consistent evidence that the APE of plant physical capacity has a statistically significant effect on the probability of shutdown, the coefficients on the interaction between plant physical capacity and the indicator for the early months of the pandemic are significant. Fig. 6 indicates that relative to March 2021, larger plants were more likely to shut down than smaller plants in April, May, and June 2020.[9] This effect disappears in most later months, suggesting plant physical capacity had a stronger effect on shutdowns at the start of the pandemic.

While the onset of the COVID-19 pandemic led to some packing plant closures, plants temporarily close for many reasons. For example, the coefficient on the interaction between plant capacity and the August 2020 indicator is statistically significant in part due to some large plants closing for a floating holiday. Our results on the effect of plant size on plant shutdowns are roughly consistent with those of Bina et al. (2022), who examine the role of regional reliance on large beef packing plants in reducing cattle slaughter rates in 2020 compared to 2019. They find that having a larger share of slaughter occurring at large plants (processing greater than 2,000 and 5,000 head/day) has a statistically significant effect for two four-week periods early in the pandemic (March 28–April 18 and May 23–June 13), but not in later periods.

6. Policy implications

Packing plants cannot operate efficiently without sufficient labor, and worker shortages in plants affect the entire meat supply chain—-from hog farmers to pork consumers. The crucial role of labor became apparent to the public when the COVID-19 pandemic forced packing plants to reduce, and sometimes temporarily halt, production. These supply disruptions contributed to wholesale and retail meat price spikes.

The federal government and university extension programs have introduced public policies, funding initiatives, and research agendas designed to improve labor availability in meatpacking and affordable housing in rural areas. Part of the Biden-Harris administration's plan dedicated $1 billion in American Rescue Plan funds to expand independent meat processing capacity, committing $100 million to support workforce training, safe workplaces, and good-paying, quality jobs (The White House, 2022). Responding to a request for public input about USDA's plan to improve meat and poultry processing infrastructure, Michigan State University Extension emphasized the critical role of training and workforce development in producing meat and poultry products. Suggestions for USDA included funding for training programs for meat cutters at high schools, community colleges, and universities (USDA, 2022b).

The U.S. meatpacking industry has long employed immigrant workers (Artz, 2012) and relies on foreign labor to offset existing labor shortages. Boessen et al. (2021) explain that improving economies, better job prospects, and rapidly falling population growth in immigrant-sending countries are changing the incentives of potential immigrants, possibly reducing foreign workers who seek U.S. agricultural jobs. However, changes to the visa classifications affecting temporary workers could partially offset decreases in the foreign labor supply. Policies related to temporary worker visa programs have been introduced to Congress in recent years but have failed to become law. In

[9] The complete coefficient table is in Appendix A.

2021, the U.S. House of Representatives approved the Farm Workforce Modernization Act (H.R.1603),[10] which includes provisions related to the H-2A temporary worker visa program. Currently, the program is not subject to annual caps, but employers can only hire H-2A foreign workers for temporary, seasonal farm jobs. Under H.R.1603, the H-2A program would be available for agricultural work year-round.

The passage of H.R.1603 could help alleviate labor shortages on livestock farms; however, worker availability in packing plants would most likely remain unchanged, as packing plant jobs fall under the H-2B worker program, a program for temporary non-agricultural workers subject to a statutory annual cap of 66,000 workers (Bruno, 2020). In addition to the proposed changes to the H-2A visa program through legislation, changes to the H-2B program have occurred as recently as 2022. More specifically, the Secretary of Homeland Security exercised his time-limited Fiscal Year (FY) authority to increase the number of H-2B visas by 65,000 for FY 2023 in addition to allowing H-2B workers who are already in the United States to begin work immediately after a H-2B visa petition (USDHS, 2022). These changes to the H-2B visa program could improve short-term labor availability in packing plants and increase hiring flexibility in times of worker shortages, potentially reducing the impacts of labor-related shocks. Having an additional, more stable source of labor could mitigate the effects of a plant being located in a population loss area—a factor we find negatively impacts slaughter rates at pork processing facilities. Industry experts and associations, such as the National Pork Producer Council, support proposed visa system reforms providing agricultural employers with sustained access to year-round labor (e.g., H-2A visa expansion to year-round labor), a pathway to legal status for agricultural workers already in the United States, and the categorization of packing plant workers as agricultural labor, a classification change that would make foreign packing plant workers eligible for the H-2A visa program (National Pork Producers Council, 2023).

Bills related to the Farm Workforce Modernization Act include the Strategy and Investment in Rural Housing Preservation Act of 2021 (H. R.1728) and 2022 (S.4872), introduced, but not voted on, in the House and the Senate, respectively. The purpose of these bills is to protect affordable rural housing, provide funding for rental assistance, and require USDA to plan for the preservation of rural housing properties. Jointly, these initiatives seek to improve labor shortages and improve housing conditions in rural areas, possibly making these areas more attractive to residents. Our findings suggest population loss is detrimental to packing plants' processing levels; and, therefore, improvements to local economic conditions may help retain residents and attract a younger workforce.

Another way to address packing plants' reliance on labor is to increase automation. Several competing perspectives exist about the extent to which capital investments alter labor needs. Newer technology and improved plant layouts could reduce labor needs, but changes in employment may be subtle due to underemployment already at many plants. Substitution of capital and technology for labor and management could be an advantage for larger plants with better access to credit and scale economies. However, substantial investments in labor-saving technologies require more highly skilled labor, altering the mix of employees needed. USDA plans to invest an estimated $50 million of the $1 billion in American Rescue Plan funds in technical assistance and research and development to help create new capacity or expand existing capacity (The White House, 2022), which plants could use to increase automation. Lusk and Tonsor (2020) indicate that advancements in robotics and data analytics tools are beginning to allow more automation in the processing of animal carcasses. In addition, changes in technology and automation could help diminish the effect of age of the plant on reductions in quantity slaughtered.

While the COVID-19 pandemic disrupted supply chains and meatpacking uniquely, infectious disease outbreaks and severe weather will continue to occur. Scientists at the Environmental Protection Agency (EPA) forecast with a high degree of confidence more frequent and intense heat waves, extreme winter precipitation events, extreme rainfall, and wildfires in the United States (EPA, 2022). Our findings indicate that reductions in slaughter when a disaster occurs can be large, reducing slaughter volumes close to 40% on average. If disasters become more frequent, the industry will be negatively impacted. Our work motivates additional research into the effects of these climate episodes on meatpacking and aligns with the USDA's Climate Change Adaptation Plan. Under this plan, USDA will develop, implement, and evaluate actions to minimize climate-associated risks (USDA, 2021b). In addition, bills that improve economic conditions in rural areas could reduce worker shortages during severe weather events. If workers can find affordable housing and other amenities in close proximity to a pork plant, employee absences because of a weather-related travel advisory may be reduced.

7. Conclusions

In this study, we not only confirm the importance of labor and population trends on meatpacking operations, but we also quantify the effect of these characteristics on different measures of production using plant-level panel data. Increases in the average number of COVID-19 cases at the county level as well as the presence of severe weather events, both of which disrupt labor availability, have a detrimental impact on processing capabilities. Plants located in population-loss areas and those farther from metro areas were also particularly vulnerable during the COVID-19 pandemic, stressing the importance of the economic conditions surrounding a packing plant. Our contribution to the literature and the policy debate encompassing meatpacking lies in our finding that the meatpacking industry, an essential part of the meat supply chain, relies on adequate labor supply in the rural areas in which plants are located.

Much of the discussion on resiliency of the industry focuses on the role of plant size. As the meatpacking sector moves forward, the sector's major vulnerabilities may not necessarily be addressed by increasing plant physical capacity. Based on our results, larger plants may have been more likely to shut down in the earliest months of the pandemic, but not over the entire study period. In contrast, factors that affect the labor markets impacted production throughout the pandemic. Future shocks and long-term trends that reduce the availability of labor, particularly in thin local labor markets, will continue to have unfavorable effects on the sector and, therefore, the entire meat supply chain. This study shifts the conversation back to labor shortages, disasters, and long-term population trends that have a quantifiable effect on processing levels.

The findings and subsequent policy discussions of this work suggest more research in this area is needed. Although we distinguish between periods early in the pandemic in which shutdowns were frequent and later periods when they were less frequent in some of our analyses, we are unable to identify reasons why shutdowns became less frequent. Possible reasons could be the effectiveness of COVID-19 health precautions, information on how the diseases spreads, and/or plant-level investments in disease prevention and management. This could also help explain some of our results, such as why large plants experienced more reductions in slaughter, and why older plants had fewer reductions. Research could also focus on other types of meatpacking plants—heterogeneity in automation and labor practices can help determine whether beef and poultry packing plants experienced similar disruptions during the pandemic, compared to pork packing plants. Finally, future research should dive deeper into the role of labor availability, including immigration, and the effects of changes to visa worker programs on addressing the labor shortages in meatpacking.

[10] This bill has passed the House of Representatives but has not passed the Senate.

CRediT authorship contribution statement

Samantha L. Padilla: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization, Supervision, Data curation. **Matthew J. MacLachlan:** Validation, Investigation, Writing – original draft, Writing – review & editing. **Kate Vaiknoras:** Investigation, Writing – original draft, Writing – review & editing. **Lee L. Schulz:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A:. Full coefficient tables

(See Tables A1 and A2).

Table A1
Coefficient results from probit (first hurdle), truncated normal (second hurdle) and the double hurdle model of quantity reduced.

VARIABLES	(1) Probit	(2) Truncated normal	(3) Double hurdle (quantity reduced)	(4) Double hurdle (participation decision)
Average COVID-19 cases in the county (1,000 cases)	0.035***	323.8	323.8	0.035***
	(0.013)	(242.1)	(241.8)	(0.013)
Plant capacity (hogs processed/day)	6.19e-06	0.0156	0.0156	6.19e-06
	(2.96e-05)	(0.211)	(0.210)	(2.96e-05)
January 2021	0.026	−6,914*	−6,914*	0.026
	(0.210)	(4,167)	(4,160)	(0.210)
February 2021	0.285	−40.85	−40.85	0.285
	(0.211)	(4,165)	(4,159)	(0.211)
April 2020	0.376	−907.0	−907.0	0.376
	(0.538)	(6,319)	(6,309)	(0.538)
May 2020	0.0221	−4,000	−4,000	0.0221
	(0.551)	(5,310)	(5,302)	(0.551)
June 2020	−0.237	−10,896**	−10,896**	−0.237
	(0.582)	(4,463)	(4,456)	(0.582)
July 2020	0.011	−8,899**	−8,899**	0.011
	(0.563)	(4,446)	(4,439)	(0.563)
August 2020	−0.105	−5,016	−5,015	−0.105
	(0.475)	(3,737)	(3,731)	(0.475)
September 2020	−0.159	−3,287	−3,287	−0.159
	(0.498)	(3,382)	(3,376)	(0.498)
October 2020	−0.588	−1,900	−1,900	−0.588
	(0.585)	(2,845)	(2,841)	(0.585)
November 2020	−0.660	−857.8	−857.8	−0.660
	(0.525)	(3,533)	(3,527)	(0.525)
December 2020	−0.106	2,256	2,256	−0.106
	(0.355)	(4,951)	(4,943)	(0.355)
January 2021 × plant capacity	−2.98e-06	0.934***	0.934***	−2.98e-06
	(1.07e-05)	(0.235)	(0.235)	(1.07e-05)
February 2021 × plant capacity	3.48e-06	0.176	0.176	3.48e-06
	(1.30e-05)	(0.248)	(0.247)	(1.30e-05)
April 2020 × plant capacity	5.75e-05***	0.458**	0.458**	5.75e-05***
	(2.08e-05)	(0.219)	(0.218)	(2.08e-05)
May 2020 × plant capacity	0.0002***	0.425**	0.425**	0.0002***
	(3.24e-05)	(0.202)	(0.201)	(3.24e-05)
June 2020 × plant capacity	0.0001***	0.547***	0.547***	0.0001***
	(2.91e-05)	(0.203)	(0.203)	(2.91e-05)
July 2020 × plant capacity	3.45e-05	0.564**	0.564**	3.45e-05
	(3.36e-05)	(0.235)	(0.235)	(3.36e-05)
August 2020 × plant capacity	3.31e-05	0.474**	0.474**	3.31e-05
	(3.57e-05)	(0.210)	(0.210)	(3.57e-05)
September 2020 × plant capacity	3.22e-05	0.356*	0.356*	3.22e-05
	(3.80e-05)	(0.200)	(0.200)	(3.80e-05)
October 2020 × plant capacity	3.66e-05	0.290	0.290	3.66e-05
	(4.50e-05)	(0.189)	(0.189)	(4.50e-05)
November 2020 × plant capacity	4.23e-05	0.203	0.203	4.23e-05
	(4.31e-05)	(0.198)	(0.198)	(4.31e-05)
December 2020 × plant capacity	3.10e-05	0.051	0.051	3.10e-05
	(2.31e-05)	(0.227)	(0.227)	(2.31e-05)
Distance to the closest metro area	0.181**	1,352***	1,352***	0.181**
	(0.073)	(458.6)	(457.9)	(0.073)
Age (log)	0.379*	1,809**	1,809**	0.379*
	(0.223)	(796.2)	(795.0)	(0.223)
Corporation	−1.135**	3,372	3,372	−1.135**
	(0.572)	(2,932)	(2,928)	(0.572)
Stay-at-home order	−0.455*	3,041**	3,041**	−0.455*
	(0.255)	(1,501)	(1,498)	(0.255)
Number of small pork plants in the area	0.0121	−499.4	−499.4	0.0121
	(0.103)	(319.3)	(318.8)	(0.103)

(continued on next page)

Table A1 (*continued*)

VARIABLES	(1) Probit	(2) Truncated normal	(3) Double hurdle (quantity reduced)	(4) Double hurdle (participation decision)
Disaster	0.361	11,678***	11,678***	0.361
	(0.531)	(3,980)	(3,974)	(0.531)
Disaster × plant capacity	1.78e-05	−0.275**	−0.275**	1.78e-05
	(2.70e-05)	(0.117)	(0.117)	(2.70e-05)
Number of unemployed (log)	0.0458	5,205	5,205	0.0458
	(0.486)	(4,416)	(4,409)	(0.486)
Population loss indicator	0.446	4,331***	4,331***	0.446
	(0.529)	(731.6)	(730.5)	(0.529)
Constant	−26.08	148,818*	148,817*	−26.08
	(21.02)	(88,746)	(88,613)	(21.02)
Observations	9,789	1,806	9,789	9,789

Note: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A2
Coefficient results from CRE probit model of shutdown.

VARIABLES	CRE probit
Average COVID-19 cases in the county (1,000 cases)	−0.002
	(0.034)
Plant capacity (1,000 hogs processed/day)	−0.0001*
	(6.64e-05)
January 2021	−0.268
	(0.420)
February 2021	0.100
	(0.361)
April 2020	−0.479
	(0.404)
May 2020	−0.914
	(0.593)
June 2020	−1.628**
	(0.698)
July 2020	−0.745
	(0.457)
August 2020	−1.77***
	(0.587)
September 2020	−1.354*
	(0.787)
October 2020	−1.137*
	(0.612)
November 2020	−0.522
	(0.588)
December 2020	−0.309
	(0.517)
January 2021 × plant capacity	0.0001
	(6.87e-05)
February 2021 × plant capacity	5.01e-05
	(6.67e-05)
April 2020 × plant capacity	0.0002**
	(6.24e-05)
May 2020 × plant capacity	0.0002**
	(6.95e-05)
June 2020 × plant capacity	0.0001*
	(7.87e-05)
July 2020 × plant capacity	0.000108
	(7.00e-05)
August 2020 × plant capacity	0.000176**
	(7.16e-05)
September 2020 × plant capacity	0.0001*
	(7.89e-05)
October 2020 × plant capacity	0.0001
	(7.40e-05)
November 2020 × plant capacity	9.83e-05
	(7.56e-05)
December 2020 × plant capacity	9.74e-05
	(6.81e-05)
Distance to the closest metro area (10 miles)	0.127**
	(0.0515)
Age (log)	−0.175**

Table A2 (*continued*)

VARIABLES	CRE probit
	(0.0885)
Corporation	−0.017
	(0.234)
Stay-at-home order	0.146
	(0.194)
Number of small pork plants in the area	−0.021
	(0.067)
Disaster	1.526**
	(0.616)
Disaster × plant capacity	−1.97e-05
	(3.85e-05)
Number of unemployed (log)	0.712
	(0.468)
Population loss indicator	0.453**
	(0.195)
Constant	−19.52
	(17.71)
Observations	9,036

Notes: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Appendix B:. Estimations using alternative definitions of neighboring counties

This section presents estimation results using different definitions of what constitutes a local area. We consider five alternative definitions: counties whose borders are within a 10-mile, 20-mile, 30-mile, 40-mile, or 50-mile radius from the plant's location. Tables B1 and B2 show the APEs from the correlated random effects double hurdle model examining slaughter reductions. Several APEs of interest are largely consistent across different local area sizes, both in terms of sign and magnitude, although the statistical significance varies. For example, the APEs of plant capacity on the probability of reducing slaughter is statistically significant for all local area sizes considered except when the local area is a 30-mile radius from the plant's location. Similarly, the APE of age on the probability of reducing slaughter oscillates between not statistically significant and statistically significant at the 10% level, depending on the size of the area. Some of the variation in statistical significance can be attributed to the size of an area. For example, the APE of the presence of a disaster on the probability of reducing slaughter is not statistically significant when the area is smaller (10- and 20-mile radius). This change in statistical significance could be because such a small area does not adequately capture the probability of reducing slaughter because of a disaster. However, the overall effect (the unconditional mean of quantity reduced) is statistically significant for all areas considered.

Table B3 displays the APEs from the CRE probit examining the likelihood of a plant shutting down. The APE of disaster on the

Table B1
Estimated APEs for the double hurdle model (10- and 20- mile radius around the location of plants in the dataset).

Counties within a:	10-mile radius of plant location			20-mile radius of plant location		
	(1)	(2)	(3)	(4)	(5)	(6)
	Prob. of reduction	Cond. mean of quantity reduced	Uncond. mean of quantity reduced	Prob. of reduction	Cond. mean of quantity reduced	Uncond. mean of quantity reduced
Plant characteristics						
Plant capacity (1,000 hogs processed/day)	0.114***	83.7*	63.9***	0.009***	162***	66.4***
	(0.003)	(45.2)	(18.1)	(0.003)	(34.7)	(16.1)
Age (log)	0.034	1,269***	375.1***	0.064*	944.6***	440.0***
	(0.029)	(287.8)	(122.1)	(0.038)	(354.0)	(167.5)
Corporation	−0.162*	794.3	−520.6	−0.180**	1,633	−446.6
	(0.082)	(1,021)	(368.9)	(0.092)	(1,192)	(428.2)
Distance to the closest metro area (10 miles)	0.007	610.8***	142.3*	0.023*	494.4***	187.6***
	(0.018)	(118.6)	(83.37)	(0.013)	(129.6)	(58.40)
Area characteristics						
Disaster	0.051	4,816**	1,427***	0.043	4,739**	1,333***
	(0.0380)	(2,302)	(518.6)	(0.037)	(2,310)	(501.5)
Number of unemployed persons (log) in area	−0.040	1,511	111.9	−0.010	2,342	391.1
	(0.080)	(1,720)	(509.2)	(0.085)	(2,042)	(561.4)
Population-loss area indicator	−0.109	3,194***	136.7	0.069	1,981***	656.3*
	(0.086)	(618.1)	(410.4)	(0.089)	(269.8)	(385.1)
Number of small pork plants in area	−0.013	782.0***	90.28	−0.0098	−190.3	−76.21
	(0.033)	(203.8)	(135.6)	(0.018)	(149.4)	(85.62)
County and state characteristics						
Average COVID-19 cases in county (1,000 cases)	0.007***	172.8	59.73**	0.007***	155.5	57.01**
	(0.0021)	(111.0)	(25.76)	(0.002)	(112.9)	(26.57)
Stay-at-home order	−0.078*	1,199*	−101.6	−0.074*	1,309**	−62.76
	(0.044)	(664.0)	(243.9)	(0.043)	(631.9)	(229.6)
Observations	9,789	1,806	9,789	9,789	1,806	9,789

Notes: Clustered-standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We omit some of the not statistically significant variables and the state and monthly controls. Full coefficient and APE tables available upon request.

Table B2
Estimated APEs for the double hurdle model (30-, 40-, and 50- mile radius around the location of plants in the dataset).

Counties within a:	30-mile radius of plant location			40-mile radius of plant location			50-mile radius of plant location		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent variable:	Prob. of reduction	Cond. mean of quantity reduced	Uncond. mean of quantity reduced	Prob. of reduction	Cond. mean of quantity reduced	Uncond. mean of quantity reduced	Prob. of reduction	Cond. mean of quantity reduced	Uncond. Mean of Quantity Reduced
Plant characteristics									
Plant capacity (1,000 hogs processed/day)	0.004	124.0***	39.3**	0.006**	151.0***	55.5***	0.0054*	178.0***	56.9***
	(0.003)	(46.0)	(18.9)	(0.003)	(42.4)	(15.0)	(0.003)	(38.5)	(16.6)
Age (log)	0.044*	839.8***	341.1***	0.036	1,180***	368.7***	0.026	1,259***	339.7***
	(0.023)	(302.7)	(102.5)	(0.028)	(359.1)	(116.9)	(0.028)	(320.6)	(128.1)
Corporation	−0.099	1,163	−207.2	−0.123	−950.7	−686.2	−0.099	−1,399	−671.0
	(0.082)	(997.0)	(381.3)	(0.097)	(1,252)	(418.2)	(0.099)	(872.3)	(440.6)
Distance to the closest metro area (10 miles)	0.014	371.1**	130.1*	0.0196	153.0	109.9	0.015	407.2***	135.7*
	(0.014)	(158.3)	(72.48)	(0.018)	(217.8)	(89.26)	(0.017)	(129.9)	(72.99)
Area characteristics									
Disaster	0.104*	3,135**	1,355**	0.098**	2,369*	1,098**	0.095**	2,376*	1,079**
	(0.062)	(1,305)	(552.7)	(0.049)	(1,418)	(492.1)	(0.048)	(1,425)	(482.1)
Number of unemployed persons (log) in area	−0.0028	2,562	457.4	−0.004	2,064	362.2	−0.006	1,977	339.2
	(0.085)	(2,246)	(573.2)	(0.089)	(2,506)	(633.9)	(0.092)	(2,613)	(652.6)
Population-loss area indicator	0.602***	−83,930	−12,836	0.163	−5,306***	−295.3	0.198	−5,363***	−167.1
	(0.129)	(61,359)	(11,298)	(0.173)	(1,489)	(795.9)	(0.189)	(1,025)	(857.6)
Number of small pork plants in area	0.008	−501.9**	−58.67	0.005	−553.1**	−81.66	0.010	−657.8***	−78.99
	(0.014)	(195.5)	(78.02)	(0.016)	(233.5)	(84.76)	(0.0197)	(163.6)	(92.10)
County and state characteristics									
Average COVID-19 cases in county (1,000 cases)	0.006***	125.3	46.88**	0.006***	124.8	47.76**	0.006***	133.5	49.76**
	(0.002)	(101.6)	(23.73)	(0.002)	(103.8)	(23.93)	(0.002)	(105.0)	(24.01)
Stay-at-home order	−0.074*	1,383**	−58.96	−0.075*	1,392**	−57.19	−0.076*	1,410**	−56.63
	(0.045)	(648.1)	(240.4)	(0.043)	(660.9)	(234.2)	(0.043)	(648.3)	(231.8)
Observations									

Notes: Clustered-standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We omit some of the not statistically significant variables and the state and monthly controls. See Appendix A for coefficient table.

Table B3
Averagepartial effects (dependent variable: plant shutdowns), for 10-, 20-, 30-, 40-, and 50- mile radius around the location of plants in the dataset.

Counties within a:	10-mile radius of plant location	20-mile radius of plant location	30-mile radius of plant location	40-mile radius of plant location	50-mile radius of plant location
	(1)	(2)	(3)	(4)	(5)
Plant capacity (1,000 hogs processed/ day)	0.0001	0.0002	0.0004	0.0004	0.0001
	(0.00092)	(0.0008)	(0.0009)	(0.0009)	(0.0008)
Age (log)	−0.004	−0.007*	−0.002	−0.002	−0.003
	(0.004)	(0.004)	(0.003)	(0.004)	(0.005)
Corporation	−0.006	−0.002	0.005	−0.001	−0.001
	(0.011)	(0.01)	(0.012)	(0.014)	(0.015)
Distance to the closest metro area (10 miles)	0.005*	0.005**	0.002	0.001	0.002
	(0.003)	(0.002)	(0.003)	(0.003)	(0.003)
Disaster	0.050*	0.048	0.110**	0.104**	0.105**
	(0.030)	(0.030)	(0.050)	(0.048)	(0.047)
Number of unemployed persons (log) in area	0.035**	0.029*	0.022	0.023	0.016
	(0.017)	(0.017)	(0.021)	(0.024)	(0.025)
Population-loss area indicator	0.032*	0.018**	0.088***	0.001	0.006
	(0.016)	(0.007)	(0.029)	(0.031)	(0.033)
Average COVID-19 cases in county (1,000 cases)	0.0004	0.0002	0.0001	0.0002	0.0002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Stay-at-home order	0.005	0.00588	0.004	0.005	0.005
	(0.008)	(0.007)	(0.008)	(0.008)	(0.008)
Observations	9,036	9,036	9,036	9,036	9,036

Notes: Clustered-standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We omit some of the not statistically significant variables and the state and monthly controls. See Appendix A for coefficient table.

probability of shutting down remains largely consistent across specifications, while population loss is statistically significant when the local area is smaller. The changing statistical significance can be partly explained fewer plants in the sample being a population loss area when the area is larger. A local area is less likely to experience consistent population decline if it is larger, as it might include a metropolitan area.

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