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Regional and plant-size impacts of COVID-19 on beef processing

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ABSTRACT

During the COVID-19 pandemic, U.S. consumers witnessed changes in the volume and type of meat products available at retail and food service markets. Simultaneously, widening farm-to-wholesale price spreads fueled calls for industry change and several related policy proposals. The objective of this study is to document fed cattle slaughter and evaluate the structure and performance of the beef processing industry during the early stages of the COVID-19 pandemic. For major beef-producing regions, the 2019–2020 change in federally inspected U.S. cattle slaughter volumes varied in isolated instances with regional reliance on larger processing facilities. Implications of this are discussed both for current policy and industry discussions, as well as to encourage additional future research.

1. Introduction

Coronavirus Disease 2019 (COVID-19) was declared a global pandemic on March 11, 2020 by the World Health Organization (World Health Organization, 2020). Within a few weeks' time, COVID-19 outbreaks began to cause the temporary closure or severely reduced operations of several meat processing plants. Disruptions in beef processing fueled calls for change to the industry, such as reducing the reliance on large processing facilities—with various government policies developed to achieve that goal (e.g., Bustillo, 2020; Linnekin, 2020; USDA, 2021). However, it is unclear if a shift in processing volume to more localized, and possibly smaller, processing plants would have made the industry less susceptible to pandemic-induced disruptions (Rude, 2020). Further, the economic forces that drove the industry's development are often overlooked. Higher-capacity federally inspected slaughter plants built in the Midwest and Southern Great Plains over the past several decades accommodate the larger supplies of fed cattle in these regions. These higher capacities result in greater processing efficiency and reduced costs—a phenomenon likewise observed in the consolidation of pork and poultry processing (e.g., Azzam and Schroeter, 1995; Gwin et al., 2013; MacDonald et al., 2000; Ollinger, MacDonald, and Madison, 2005). Policy prescriptions to the COVID-19 pandemic or similar action to alter the structure of the industry may undermine these developments, resulting in adverse cost implications to the entire supply chain.

A careful balance must be struck between efficiency in meat production during "normal times" with increased system resiliency during pandemics and other possible major disruptions (Tonsor and Schulz, 2020a). In pursuit of this goal, multiple knowledge gaps must be addressed to inform a broader benefit-cost assessment of any proposed industry changes. As part of this, we must better understand how the current structure of the industry performed during COVID-19-related production challenges and quantify how the reliance on large processing facilities impacted the ability to harvest live animals during this time. To do so, we leverage region-level data, as opposed to the national aggregates commonly used in related work. This allows for assessment of each region's production during the onset of the COVID-19 pandemic and for empirical analysis of the varying regional reliance on large processing facilities. This increased understanding can underpin improved assessment of several governmental policies developed following COVID-19-related production challenges such as: the invocation of the Defense Production Act to classify meat processing plants as essential infrastructure (Telford et al., 2020), the U.S. Department of Agriculture (USDA) investing $500 million in American Rescue Plan funds to expand physical meat processing capacity (USDA, 2021), and various other state-level initiatives intended to increase local physical processing capacity.

This study, motivated by concerns over the structure of the beef processing industry and a need for data-driven research to inform policy assessment, is organized as follows. First, we provide a brief summary of

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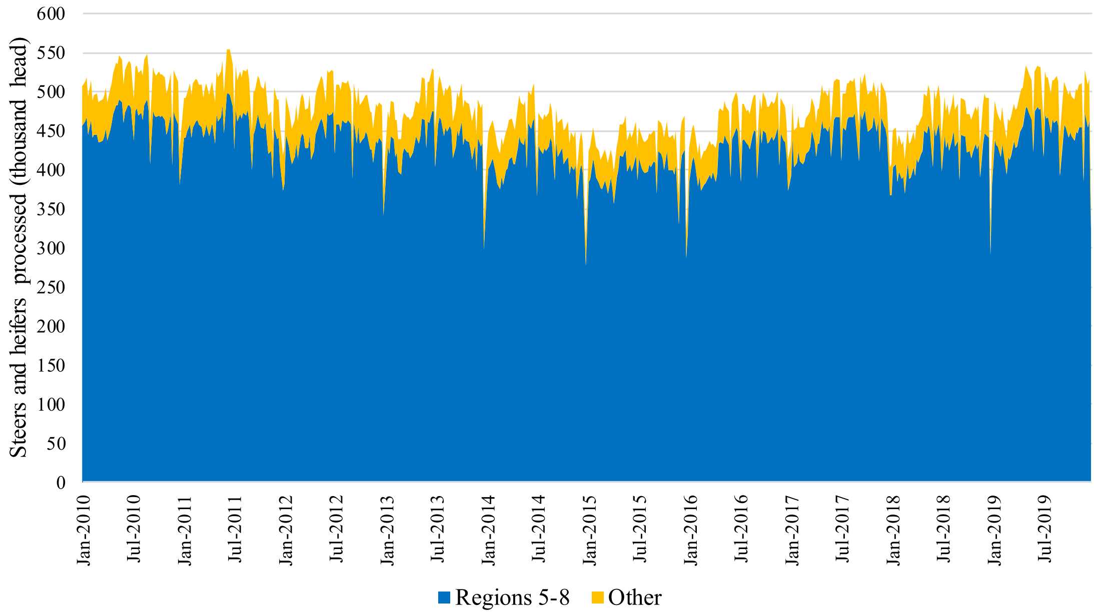

Fig. 1. Weekly National FI Steer and Heifer Slaughter, 2010–2019.

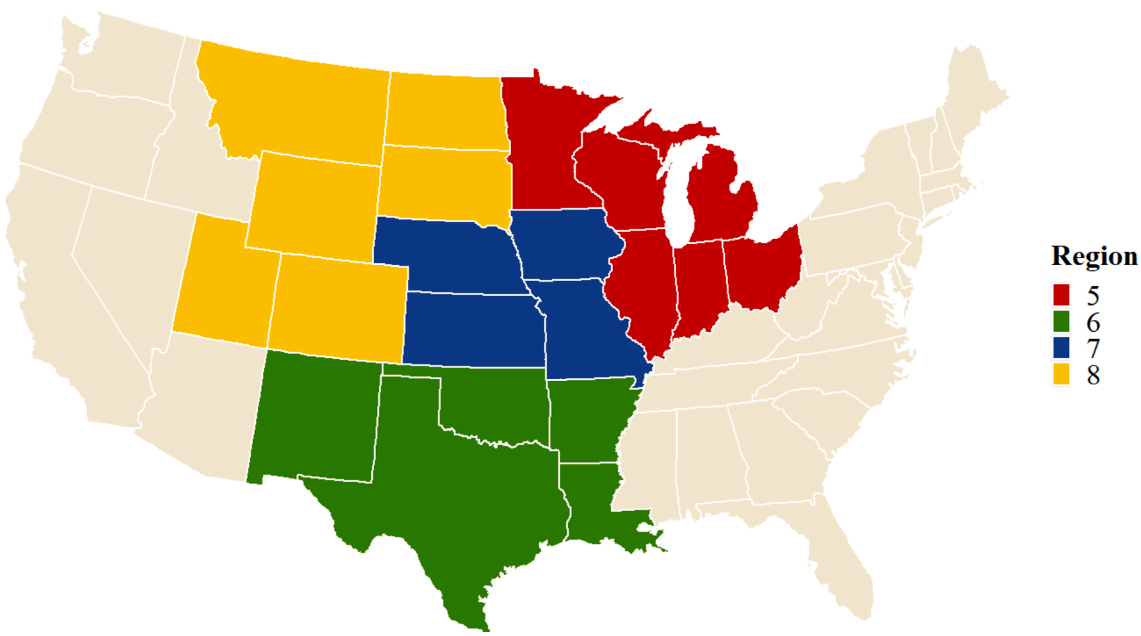

Fig. 2. U.S. Standard Federal Regions.

workforce shortages occurring in the meat processing sector during COVID-19. Then, we give a history of cattle slaughter levels for the years leading into 2020 followed by an overview of national and regional impacts of COVID-19 on cattle harvest. Finally, using regional data, we conduct an empirical analysis of plant-size effects on cattle harvest during COVID-19 and conclude with results and implications.

2. COVID-19 impacts on labor in the meat processing sector

The COVID-19 pandemic highlighted vulnerabilities in labor-intensive industries. This was especially apparent in the meat processing sector, where the efficient operation of processing plants is dependent upon the availability of workers trained in the diverse set of tasks required to harvest animals and process them into meat products (Tonsor and Schulz, 2020a). The meat processing sector, in contrast to some other industries, experienced high worker absenteeism. This was exacerbated by an already tight labor supply, which collectively limited the number of workers to draw upon. For instance, even if plants had enough labor to operate kill floors, many were short of labor on boning lines and in by-product capture operations. Further, attempts by plant managers to mitigate the health risk to workers—including social distancing requirements, assignment and quarantine of workers by group, and temporary plant closures—amplified bottlenecks experienced in processing (Luckstead et al., 2021).

From April to June 2020, over 80 beef and pork processing plants had reported confirmed cases of COVID-19, with about 10% of employees at these facilities testing positive on average according to a report by the Federal Reserve Bank of Kansas City (Cowley, 2020). Some

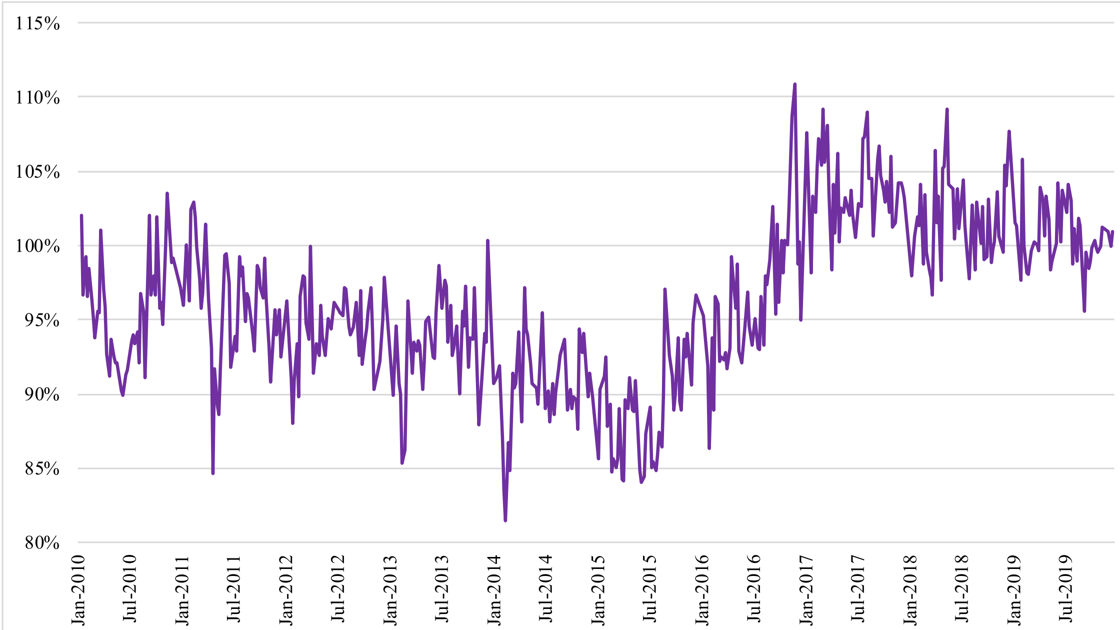

Fig. 3. Beef Processing Industry Utilization-to-Capacity Ratio, 2010–2019.

plants experienced 30% to 70% of their workforce affected by the virus and almost half the plants with outbreaks halted production, resulting in temporary oversupply of live animals and higher meat prices for consumers (Cowley, 2020). With meat and poultry plants accounting for nearly a third of the 1.7 million U.S. food and beverage manufacturing employees as of 2018 (USDA-ERS, 2018), labor shortages in the sector place a substantial strain on the U.S. food system and consumers' access to many food items.

3. Cattle harvest pre-COVID-19

To fully appreciate the impact of the COVID-19 pandemic on beef processing, it is important to understand the market situation and production levels heading into 2020. Fig. 1 depicts weekly national federally inspected (FI) steer and heifer slaughter from 2010 through 2019. We focus on steer and heifer (fed cattle) slaughter, as opposed to cow slaughter, as these plants tend to be larger and are far more susceptible to a tight labor market (Steiner Consulting Group, 2021). We utilize data from the USDA Agricultural Marketing Service (AMS) U.S. Federally Inspected Slaughter by Region report (SJ_LS713), which is compiled by the USDA National Agricultural Statistics Service (NASS) USDA-AMS, 2021a. Regions 5, 6, 7, and 8 accounted for 6%, 18%, 52%, and 12% of FI steer and heifer slaughter in 2019, respectively, and represent a majority of historical beef processing volume.[1] Region 5 consists of Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin (Fig. 2). Region 6 is Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Region 7 is Iowa, Kansas, Missouri, and Nebraska. Region 8 is Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming.

Weekly FI slaughter at the start of the decade was routinely over 500,000 head, peaking in June 2011 at 555,000 head processed per week. Processing volume then declined over the next several years, bottoming out at around 400,000 head per week in March and April 2015. This corresponded to the 50-year low in cattle inventories at the start of 2014 that marked the beginning of the current cattle inventory cycle (U.S. Department of Agriculture, 2021a).[2] Historically high cattle prices in 2014–2015 (U.S. Department of Agriculture, 2021b) prompted herd expansion, with FI slaughter volumes gradually increasing through the second half of the decade. By 2019, weekly slaughter numbers were approaching those experienced in 2011, again consistently over 500,000 head.

Dynamic cattle inventories have put pressure on relatively "static" beef processing capacity, resulting in more reliance on overtime production to handle high supplies. This reflects an ever-evolving relationship between the inventory of market-ready fed cattle and processing capacity. As noted by Tonsor and Schulz (2020b), early 2020 was characterized by high plant utilization as the volume of market-ready cattle was high relative to capacity. While this supported larger beef stocks when the pandemic disrupted production, it also reflects strains on the supply chain and little margin for error (Tonsor and Schulz, 2020a).

The use of weekend, normally Saturday, as a common form of overtime slaughter operations varies over time. Analysts often view weekend operations as "shock absorbers" in the industry, providing a tool to "catch-up" in holiday-shortened weeks or following other disruptions to normally planned operations. Using daily national FI slaughter numbers from the AMS Actual Slaughter Under Federal Inspection report (SJ_LS711), compiled by the Livestock Marketing Information Center (LMIC, 2021), we calculate the average share of weekly slaughter that has occurred on Saturdays over timeUSDA-AMS, 2021b. In 2015, 2.1% of weekly FI steer and heifer slaughter occurred on Saturday, on average, with this value increasing to 9.2% in 2019. Significant increases in the share of Saturday slaughter highlights the pressure processing plants faced from increasing cattle supplies, resulting in a progressively larger need to operate on weekends.

COVID-19, unlike the 2019 fire that halted operations at the Holcomb, KS Tyson plant and reduced physical beef processing capacity, was a disruption to the industry's operational capacity. Operational capacity is the amount able to be produced in a given amount of time (assuming ample cattle supplies) and is highly influenced by the supply

[1] Region 5 heifer slaughter has not been published (withheld to avoid disclosing data for individual operations) since the week ending December 30th, 2017. As such, reported slaughter for Region 5 following this date reflects steers only.

[2] Declining cattle supplies resulting from prolonged drought conditions in the Southern Plains prompted Cargill's closure of its high-volume Plainview, TX processing plant in 2013 (Cargill, 2013).

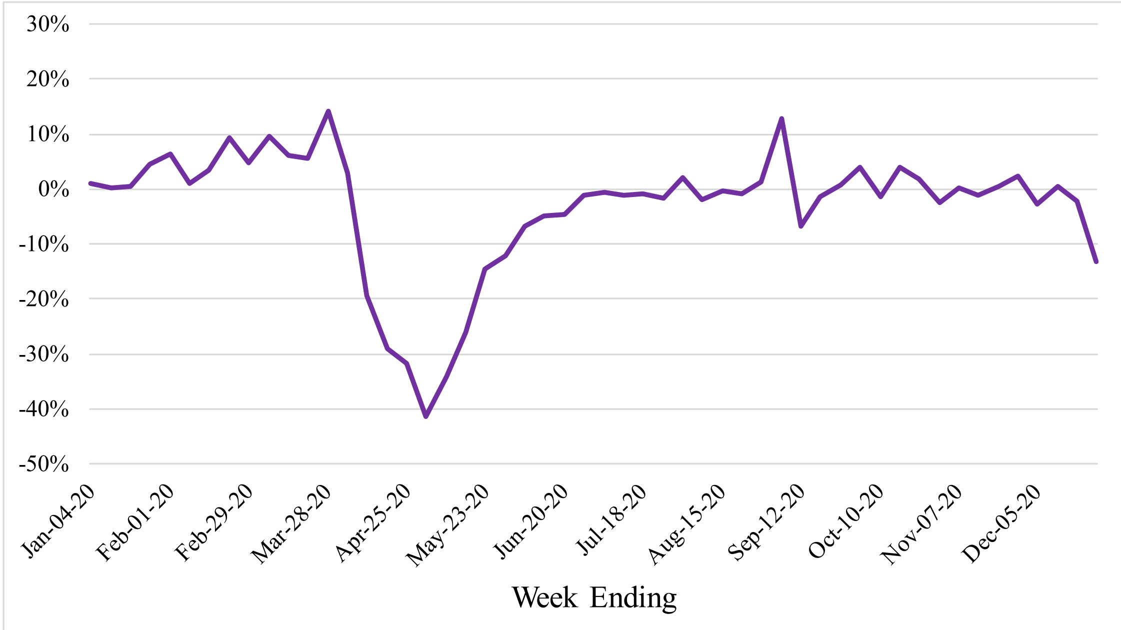

Fig. 4. Percentage Change in Weekly National FI Steer and Heifer Slaughter, 2020 vs. 2019.

of labor. To appreciate the difference, note one can have large physical capacity yet reduced operational capacity. If an industry has brick-and-mortar facilities yet insufficient personnel to fully run those facilities, this is an example of physical capacity exceeding operational capacity. This relationship is exactly what unfolded during the COVID-19 pandemic. This is important to understand as proposed solutions to improve industry resilience to major economic shocks commonly focus on increasing physical capacity in the form of numerous, smaller processing facilities. Policy prescriptions addressing physical capacity when labor is the constraint may not have their intended effect.

To better understand how the industry was producing relative to operational capacity heading into 2020, we calculate a utilization-to-capacity ratio, depicted in Fig. 3. The ratio was derived by taking current week national FI steer and heifer slaughter volume divided by the maximum FI steer and heifer slaughter volume having occurred over the prior three years for the same week, following the method implemented by Tonsor and Schulz (2020b). With no estimate of industry operational capacity readily available, we implement the maximum volume over the prior three years, by week, as a "presumed" operational capacity.[3]

Corresponding to relatively low cattle inventories in 2014, utilization bottomed out in the middle of the decade at around 85% of operational capacity. Utilization then notably increased during the latter part of the decade, fluctuating at around 100–105% leading into 2020. This mirrors the findings of Peel (2021) that slaughter has exceeded estimated steer and heifer slaughter capacity since 2016, meaning that the processing industry has met slaughter demand by extending normal operating schedules and increasing Saturday slaughter volume. Note, utilization-to-capacity can exceed 100% when a week's slaughter volume is greater than the maximum slaughter volume experienced for the same week over the prior three years (increasing Saturday slaughter could result in such a situation). This does not mean the industry exceeded its physical capacity. With high cattle supplies necessitating increased weekend operations and the beef processing industry already at an elevated utilization-to-capacity level at the start of 2020, COVID-19-related labor shortages amplified the challenge of harvesting market-ready animals in a timely fashion at the onset of the disruption (e.g., Charles, 2020; Zarroli, 2020).

4. Cattle Harvesting during COVID-19

As noted earlier, there is a key difference between physical and operational capacity. The COVID-19 pandemic induced substantial workforce shortages and, as such, reduced operational beef processing capacity. To document the resulting production impacts this had, the following sections outline national and regional reductions in cattle slaughter. The impacts may most clearly be told by evaluating year-over-year changes in slaughter levels. Year-over-year comparisons are a popular metric as the impact of seasonality is mitigated, a factor that is extremely prevalent in the cattle industry, and tells us how the period in question compares with "normal conditions" with an emphasis on the most recent prevailing market fundamentals.

4.1. National patterns

Fig. 4 depicts the percentage change in weekly national FI slaughter of steers and heifers for 2020 versus 2019, utilizing the SJ_LS713 report. Slaughter volumes at the start of 2020 averaged about 5% higher than 2019 levels, peaking to 14% higher for the week ending March 28. Impacts of the COVID-19 pandemic on beef processing plants and cattle processing began in early April with FI slaughter numbers quickly falling to 41% below that of 2019 by the week ending May 2 as temporary plant-shutdowns and reductions in operating capacity went into effect. From the weeks ending April 11 to May 30, FI steer and heifer slaughter numbers averaged 26% lower than 2019 levels for the same time period. Steer and heifer slaughter during this 8-week time period was 1.08 million head lower in 2020 relative to 2019. These reductions correspond to a backlog of nearly two weeks of typical cattle slaughter for that time of year, creating substantial strain on supply chains (Lusk, Tonsor, and Schulz, 2020).

Though impacts of plant closures on the harvest of fed cattle were rapid and extreme, note the equally rapid recovery beginning in early May. After experiencing their lowest levels for the week ending May 2, weekly steer and heifer slaughter increased 67%, or about 215,000 head, by the week ending June 27. Relative to 2019 numbers for the

[3] Private firm estimates for beef processing capacity are available, but these reflect physical, not operational, capacity. For instance, these estimates do not account for planned maintenance days or, recently, workforce vaccination days that alter operational capacity.

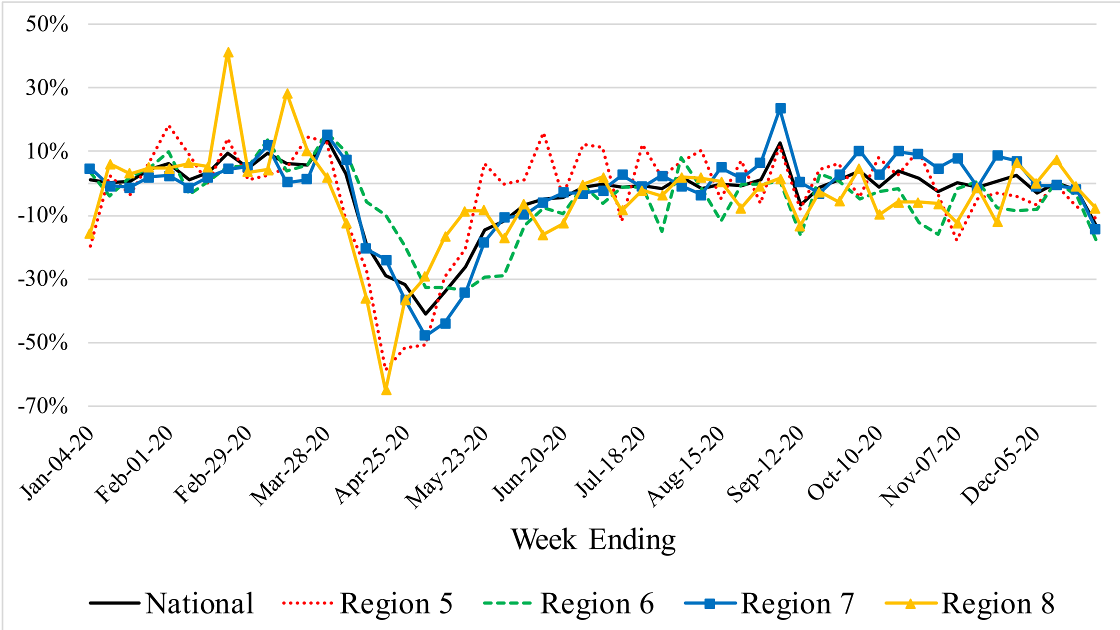

Fig. 5. Percentage Change in Weekly Regional FI Steer and Heifer Slaughter, 2020 vs. 2019.

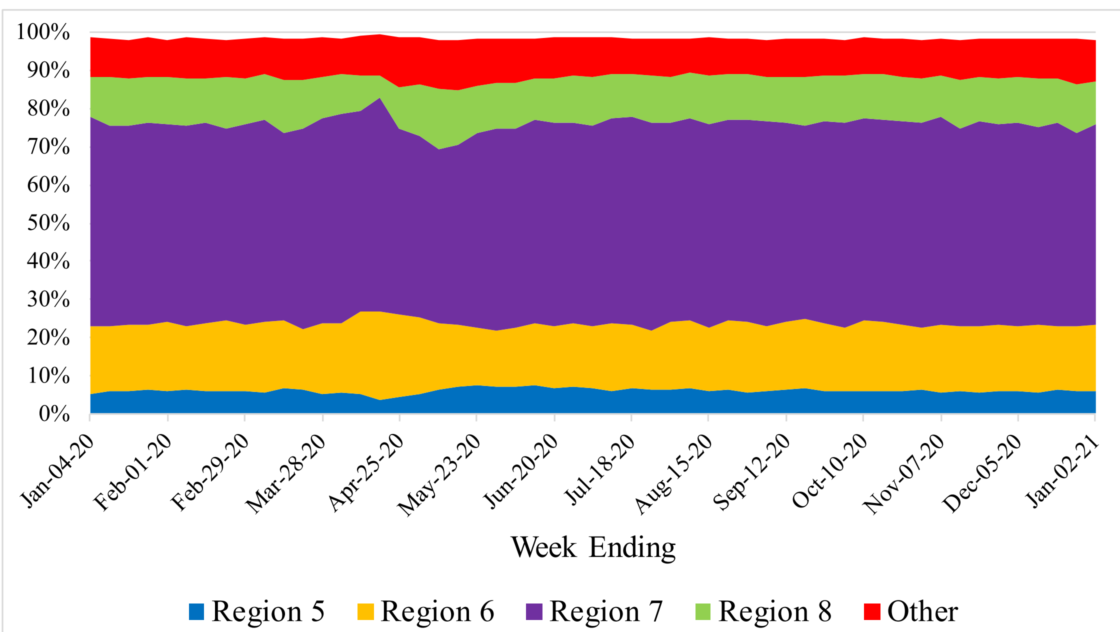

Fig. 6. Regional Share of 2020 National FI Steer and Heifer Slaughter.

same time period, it took just eight weeks to go from 41% lower 2020 FI steer and heifer slaughter to 1% lower slaughter. The “V-shaped” recovery of cattle harvest levels could be viewed as a “best case recovery scenario,” as drastic declines in FI slaughter due to COVID-19-related shutdowns and the resulting stress placed on beef supply chains were followed by slaughter growth nearly equal in speed. Steer and heifer slaughter volume was much less disrupted during the second half of 2020.[4]

Similar, rapid COVID-19 recovery stories can be told for hog slaughter and for a variety of other food sectors both domestic and international (e.g., Deconinck et al., 2020; Hayes et al., 2021; Lusk, Tonsor, and Schulz, 2020; Padilla et al., 2021; Weersink et al., 2021).

[4] The weeks ending September 5 and September 12 of 2020 (weeks 36 and 37) experienced substantial movement in FI steer and heifer slaughter as a percentage change from 2019 volume. This reflects a holiday effect as Labor Day occurred during the week ending September 7, 2019 (week 36) and week ending September 12, 2020 (week 37).

Deconinck et al. (2020) point to several mechanisms used amongst food processors to aid in the quick adaption to COVID-19-related production challenges, including increasing operating hours and reducing the variety of products to focus on those that were most popular. Weersink et al. (2021) suggests food supply chains designed for "just in time" delivery and no reserve capacity, while contributing to initial disruptions, may have also contributed to the rapid rebound in prices and production levels to those typically observed in years prior to the pandemic.

4.2. Regional patterns

In addition to national slaughter levels, regional impacts of COVID-19 on the harvest of fed cattle are important to consider. Depicted in Fig. 5 is the percentage change in weekly FI steer and heifer slaughter for 2020 versus 2019 by region. For the sake of clarity, we include only Regions 5, 6, 7, and 8 as these regions have the highest beef processing volumes and are regularly reported by USDA.

Region 5 realized steer slaughter and Region 8 realized steer and heifer slaughter for the week ending April 18 at 59% and 65% (18,000 and 39,800 head) below that of the same week in 2019, respectively. Region 6 steer and heifer slaughter did not bottom out until the week ending May 16, when it experienced slaughter levels 33% below that of 2019, or a reduction of 31,700 head. Region 7, accounting for a majority of historical FI steer and heifer slaughter, experienced slaughter volume for the week ending May 2, 2020 at 48% below that of the same week in 2019, corresponding to a 139,000 head reduction. Smaller decreases in cattle slaughter in Region 6 relative to other regions suggests that significant geographic dispersion between processing plants may have lessened the impact of COVID-19 on the national level.

Further illustrating the impacts of COVID-19 on regional cattle slaughter, Fig. 6 depicts the percentage share of national FI steer and heifer slaughter attributable to each region throughout 2020. Region 5, accounting for 5% of national slaughter in week 1 of 2020, fell to 3% by the week ending April 18. Region 6, corresponding to its relatively lower reductions in FI slaughter, realized an increase from 18% of national slaughter at the start of 2020 to 23% for the week ending April 18. Region 7′s share of national slaughter declined from 55% to begin 2020 to 46% by the week ending May 9 while Region 8′s share fell from 10% at the start of the year to 6% for the week ending April 18. The variance in timing and magnitude of cattle slaughter declines between regions (and resulting distributional effects on beef processing) may be the result of differing state and local shutdown ordinances, different COVID-19 presence, or a myriad of other possible factors.

5. Procedure

Regional slaughter and plant information, along with estimates of the share of weekly, regional operational capacity coming from large packing plants, allows us to evaluate the impact of the presence of plants varying in size on fed cattle slaughter volumes during the COVID-19 pandemic and offers insight into how the current structure of the industry performed during the major disruption. Weekly FI steer and heifer slaughter numbers for Regions 5, 6, 7, and 8 were obtained from the USDA-AMS SJ_LS713 reports compiled by USDA-NASS and percentage changes from 2019 to 2020 (*PercentChange*) were utilized as the response variable in our baseline model.[5] Sensitivity of our results were assessed using various alternatives to this response variable.

Table 1 provides a summary of the geographic dispersion of the beef industry's fed cattle processing plants as of the end of 2020 (Rabobank). An estimate of weekly, regional slaughter accounted for by 2000–4999 (5000 or more) head/day plants was derived by multiplying the number of those plants in the region by 3500 (5000) head/day and again by 5.4 working days/week. Working days per week is set at 5.4 following Meyer (2018) and was verified by sources in the beef sector. Viator et al. (2017), for example, implements a similar estimate of 5.5 working days per week.

Table 1
Regional Distribution of FI Fed Beef Packing Plants by Capacity.

Daily Slaughter Capacity (head)	Number of Plants			
	Region 5	Region 6	Region 7	Region 8
<1000	3	0	4	1
1000–1999	0	1	2	1
2000–4999	1	1	4	2
5000+	0	2	6	1

Table 2
Summary of Variables Used in Models Explaining 2020 Cattle Harvesting (vs. 2019).

Response	Description
PercentChange	% change in FI steer and heifer slaughter from 2019 to 2020, by region and week
PC_3avg	% change in FI steer and heifer slaughter from the 2017–2019 average to 2020, by region and week
PC_5avg	% change in FI steer and heifer slaughter from the 2015–2019 average to 2020, by region and week
PC_3max	% change in FI steer and heifer slaughter from the 2017–2019 maximum to 2020, by region and week
PC_5max	% change in FI steer and heifer slaughter from the 2015–2019 maximum to 2020, by region and week
HeadChange	Head change in FI steer and heifer slaughter from 2019 to 2020, by region and week
Predictor	
LaborDay	Categorical variable for weeks 36 and 37, 2020
twoKshare	% of region's presumed weekly operational capacity coming from plants with 2,000–4,999 head daily capacity
fiveKshare	% of region's presumed weekly operational capacity coming from plants with 5,000 + head daily capacity
Weeks	Categorical variables for four-week increments
twoKshare: Weeks	Interaction terms
fiveKshare: Weeks	

In addition, we utilize a 2020 presumed operational capacity, defined as each weeks' maximum FI steer and heifer slaughter volume experienced over the prior three years (2017–2019). We calculate this for each of Regions 5, 6, 7, and 8. Dividing the estimate of slaughter coming from 2000 to 4999 (5000 or more) head/day plants by the presumed operational capacity, we arrive at the share of each region's weekly operational slaughter capacity accounted for by "large" plants. These estimates are including in our empirical model as *twoKshare* and *fiveKshare*.

A categorical variable (*LaborDay*) for weeks 36 and 37 (or weeks ending September 5 and September 12, 2020) was included to account for the "holiday effect" on year-over-year slaughter, as Labor Day occurred on week 36 in 2019 and week 37 in 2020.[6] Four-week temporal categorical variables were included (e.g., *Weeks5-8*, *Weeks9-12*, etc.) to determine the timing of the "bottleneck" period—or when year-over-year FI slaughter reductions were greatest. Four-week periods were used, as opposed to manually assigning the bottleneck period, to reduce concerns of endogeneity. In other words, using changes in FI cattle

[5] Week 53, 2020 was omitted from the analysis as there was no corresponding week 53, 2019 from which to calculate percentage changes in slaughter volume.

[6] New Year's, Thanksgiving, and Christmas were also considered for potential year-over-year impacts. However, these three holidays all occurred on the same week for both 2019 and 2020, and were all on weekdays. As such, we omitted them from the estimation of "holiday effects".

slaughter to inform our specification for the bottleneck period may result in biased estimates. The variables *twoKshare* and *fiveKshare* were interacted with temporal categorical variables to determine how regional reliance on large processing plants related to slaughter difficulties during these time periods. Equation (1) depicts the baseline model where *r* represents the region, *w* represents the week, and *e* is an error term. Table 2 provides a description of the variables used as well as alternative response variable specifications.

$$\begin{aligned} PercentChange_{r,w} =& b_0 + b_1 LaborDay + b_2 twoKshare_{r,w} + b_3 fiveKshare_{r,w} \\ & + \sum_{i=1}^{12} b_{i+3} Weeks + \sum_{j=1}^{12} b_{j+15}(twoKshare_{r,w} \mathrm{x} Weeks) \\ & + \sum_{k=1}^{12} b_{k+27}\left(fiveKshare_{r,w} \mathrm{x} Weeks\right) + e_{r,w} \end{aligned} \tag{1}$$

Ideally, plant-specific production history could be used in our analysis. However, such information is not publicly available. As a compromise between firm-level data and the aggregate national data often noted in previous research, we utilize available regional slaughter information to determine COVID-19 impacts on beef processing. Summary statistics for continuous variables, along with weekly 2020 FI steer and heifer slaughter volume and presumed operational capacity, are reported by region in Appendix Table A1.

We expect the *Weeks* variables corresponding to early spring 2020 to be negative. This would reflect the reduction in 2020 slaughter volume relative to 2019 that was experienced at the onset of the COVID-19 pandemic. Of primary interest are the interactions of the *twoKshare* and *fiveKshare* variables with *Weeks* variables. Negative (positive) and statistically significant coefficients for these interaction terms imply that for greater regional reliance on large processing facilities, larger reductions (increases) in 2019–2020 slaughter volume were experienced during the production bottleneck. Interaction terms not being statistically significant for the spring time period would indicate that regional reliance on large processing facilities did not impact year-over-year changes in FI cattle slaughter early on in the COVID-19 pandemic—and further suggests that reducing the reliance on large facilities would not have alleviated labor-induced production disruptions.

6. Results

The results of our model estimating the impact of regional reliance on large processing facilities on 2020 FI cattle slaughter are reported in Table 3. *LaborDay* was not statistically significant (95 percent level), suggesting the lack of a holiday effect on 2019 to 2020 cattle slaughter during this time frame. Likely, higher 2020 slaughter in week 36 was offset by lower 2020 slaughter in week 37 (relative to 2019) and, on net, the change in slaughter volume for the two-week period was not substantial. *Weeks17-20* (corresponding to the week ending April 25 through week ending May 16, 2020) was negative and statistically significant, with the 2019 to 2020 percentage change in FI steer and heifer slaughter for Regions 5, 6, 7, and 8 falling by nearly 52 percentage points relative to the start of 2020. This matches patterns seen in previous sections of this work, as well as past research (e.g., Lusk, Tonsor, and Schulz, 2020).

Interactions of *twoKshare* with *Weeks* variables were generally not statistically significant, with the exception of *twoKshare:Weeks13-16* (corresponding to the week ending March 28 through week ending April 18, 2020) where the interaction was negative and significant at the 90 percent level. Similarly, interactions of *fiveKshare* with *Weeks* variables were generally not statistically significant, except for a significant (95% level) and negative *fiveKshare:Weeks21-24* (corresponding to the week ending May 23 to June 13, 2020). These coefficients suggest a higher reliance on large facilities yielded larger reductions in FI cattle slaughter during those two particular time frames. However; to the authors' knowledge, there is no documentation of a higher number of 2000–4999 head/day facilities closing in weeks 13 through 16, or of a higher number of 5000 or more head/day facilities closing in weeks 21 through 24.

Following statistically significant coefficients for the two aforementioned interactions, we tested the joint significance of *twoKshare*, *fiveKshare*, and all associated *Weeks* interactions (26 variables in total) to determine if industry reliance on larger processing facilities resulted in larger production disruptions during 2020. An F-test comparing our baseline model (unrestricted model) to a restricted model implementing only *LaborDay* and *Weeks* variables was statistically significant (95% level), indicating the reliance on large facilities had significant explanatory power over 2020 versus 2019 changes in FI cattle slaughter. An important consideration, however, is that statistically significant production declines (*twoKshare:Weeks13-16* and *fiveKshare:Weeks21-24*) were isolated instances. That is, all temporal and plant-share interactions following these occurrences were not statistically significant at any level. This suggests some degree of internal resiliency (i.e., an ability to quickly adjust to detrimental production challenges) amongst large processing facilities as adverse impacts were confined to 4-week periods.

Alternative measures of changes in production were incorporated to assess the sensitivity of our results. As an alternative approach to the percentage change in weekly regional FI steer and heifer slaughter from 2019 to 2020 (the response variable in the baseline model), we also considered a percentage change from: the 2017–2019 average (*PC_3avg*), the 2015–2019 average (*PC_5avg*), the maximum during 2017–2019 (*PC_3max*), and the maximum during 2015–2019 (*PC_5max*), as well as the head change in slaughter from 2019 to 2020 (*HeadChange*). Additionally, we adjusted the plant-share variables to represent 1000–4999 head/day plants and 5000 or more head/day plants (rather than 2000–4999 head/day and 5000 or more head/day). None of these adjustments altered our key conclusions regarding the relationship between slaughter volume during the COVID-19 pandemic and regional reliance on larger processing plants, providing some sensitivity robustness to our findings.

7. Implications

Given the importance of meat protein in U.S. consumer diets, economic contribution of the meat-livestock sector, and wide media coverage of pandemic impacts on the industry, it is important to carefully use available data to document and learn from the COVID-19 experience. The take-home findings of this research are twofold. First, the beef industry experienced substantial production reductions early in the pandemic as reflected in USDA-reported data. This finding is not surprising and supports previously noted research. However, the patterns highlighted here using regional data add additional important insights beyond the national patterns more often discussed. Second, there is limited statistical evidence of pandemic-induced production reductions being different for varying levels of regional reliance on larger processing facilities for most of 2020. Robustness checks reveal these two main findings are not sensitive to adjustments in how production impact is measured or how plant size details are incorporated.

The implications of these findings are far-reaching. If additional physical capacity is added to the industry, it may not provide the widely-stated benefit of increased "resiliency." It is often presumed there is a trade-off between efficiency and resiliency when considering industry structure. However, limited evidence of plant-size COVID-19 impacts for most of 2020 suggests caution in presuming this tradeoff. If this trade-off exists, our work suggests it is short-lived. An industry more reliant on larger facilities, and having economies of scale beneficial during "normal" or "peace-time" periods of operation, may be as resilient to major disruptions as a costlier industry that relies less on large facilities. This finding is consistent with the concurrent work of Ma and Lusk (2021) and related remarks made by Saitone et al. (2021). However, in

Table 3
Summary of Regression Analysis for Models Explaining 2020 Cattle Harvesting (vs. 2019).

	Dependent variable:					
	PercentChange (1)	PC_3avg (2)	PC_5avg (3)	PC_3max (4)	PC_5max (5)	HeadChange (6)
Constant	−2.14	−26.09**	−29.69**	−22.44*	−27.03**	−553.18
	(12.60)	(12.02)	(11.87)	(11.40)	(11.21)	(19,020.51)
LaborDay	−0.19	−4.18	−3.88	−2.42	−2.53	1,651.42
	(4.32)	(4.12)	(4.07)	(3.90)	(3.84)	(6,515.91)
twoKshare	−0.03	0.33*	0.31*	0.05	0.07	−14.53
	(0.20)	(0.19)	(0.18)	(0.18)	(0.17)	(294.82)
fiveKshare	0.07	0.33***	0.43***	0.34***	0.40***	41.66
	(0.12)	(0.12)	(0.12)	(0.11)	(0.11)	(184.44)
Weeks5-8	−2.29	−18.27	−8.88	−9.49	−5.86	−4,198.82
	(17.36)	(16.56)	(16.35)	(15.70)	(15.45)	(26,205.85)
Weeks9-12	−3.27	−15.98	−6.41	−12.89	−7.55	−978.24
	(17.21)	(16.41)	(16.21)	(15.57)	(15.31)	(25,979.71)
Weeks13-16	9.51	10.39	18.74	9.53	11.78	8,996.54
	(17.54)	(16.73)	(16.52)	(15.87)	(15.61)	(26,474.19)
Weeks17-20	−51.58***	−44.19***	−36.57**	−42.60***	−38.37**	−55,076.65**
	(17.23)	(16.43)	(16.22)	(15.58)	(15.33)	(26,002.98)
Weeks21-24	12.55	19.29	24.95	19.56	22.47	−9,905.08
	(18.54)	(17.68)	(17.46)	(16.77)	(16.50)	(27,986.99)
Weeks25-28	4.79	11.31	15.37	15.18	15.53	−37.22
	(18.39)	(17.54)	(17.32)	(16.64)	(16.36)	(27,758.02)
Weeks29-32	12.29	5.01	14.85	13.23	16.89	1,682.36
	(18.82)	(17.95)	(17.73)	(17.03)	(16.75)	(28,413.24)
Weeks33-36	−0.50	−6.11	5.63	0.79	4.72	−3,952.84
	(18.11)	(17.27)	(17.05)	(16.38)	(16.11)	(27,326.67)
Weeks37-40	2.92	−6.94	0.90	−3.52	3.67	174.70
	(18.16)	(17.32)	(17.10)	(16.43)	(16.16)	(27,410.34)
Weeks41-44	9.22	−0.64	9.32	0.99	3.08	328.54
	(18.27)	(17.42)	(17.20)	(16.53)	(16.26)	(27,574.92)
Weeks45-48	−3.72	−3.01	5.15	−2.34	−0.67	456.60
	(18.41)	(17.55)	(17.33)	(16.65)	(16.38)	(27,780.11)
Weeks49-52	−1.75	5.68	13.62	10.71	13.50	−357.77
	(16.73)	(15.95)	(15.75)	(15.13)	(14.88)	(25,247.52)
twoKshare:Weeks5-8	0.31	0.47*	0.28	0.21	0.19	151.34
	(0.27)	(0.26)	(0.25)	(0.24)	(0.24)	(407.69)
twoKshare:Weeks9-12	0.23	0.44*	0.28	0.34	0.30	62.15
	(0.27)	(0.26)	(0.25)	(0.24)	(0.24)	(404.15)
twoKshare:Weeks13-16	−0.51*	−0.54**	−0.64**	−0.44*	−0.47**	−272.50
	(0.27)	(0.25)	(0.25)	(0.24)	(0.24)	(403.16)
twoKshare:Weeks17-20	0.35	0.30	0.22	0.35	0.34	942.49**
	(0.27)	(0.26)	(0.26)	(0.25)	(0.24)	(414.31)
twoKshare:Weeks21-24	−0.06	−0.15	−0.18	−0.06	−0.07	252.87
	(0.29)	(0.28)	(0.27)	(0.26)	(0.26)	(436.95)
twoKshare:Weeks25-28	−0.003	−0.02	−0.06	−0.01	−0.04	26.67
	(0.29)	(0.28)	(0.27)	(0.26)	(0.26)	(436.19)
twoKshare:Weeks29-32	−0.02	0.11	−0.02	−0.04	−0.06	38.29
	(0.30)	(0.29)	(0.28)	(0.27)	(0.27)	(455.51)
twoKshare:Weeks33-36	0.07	0.24	0.06	0.13	0.10	35.76
	(0.29)	(0.27)	(0.27)	(0.26)	(0.26)	(433.76)
twoKshare:Weeks37-40	−0.01	0.25	0.13	0.13	0.05	−9.50
	(0.29)	(0.28)	(0.27)	(0.26)	(0.26)	(440.13)
twoKshare:Weeks41-44	−0.06	0.13	−0.04	0.03	0.01	−9.80
	(0.29)	(0.28)	(0.28)	(0.26)	(0.26)	(440.91)
twoKshare:Weeks45-48	−0.02	0.05	−0.07	0.001	0.003	−57.16
	(0.29)	(0.28)	(0.28)	(0.27)	(0.26)	(442.25)
twoKshare:Weeks49-52	0.03	−0.08	−0.20	−0.13	−0.17	47.03
	(0.26)	(0.25)	(0.24)	(0.23)	(0.23)	(389.03)
fiveKshare:Weeks5-8	−0.07	0.12	0.08	0.08	0.03	31.90
	(0.17)	(0.16)	(0.16)	(0.16)	(0.15)	(259.58)
fiveKshare:Weeks9-12	0.03	0.12	0.07	0.10	0.04	96.97
	(0.17)	(0.16)	(0.16)	(0.16)	(0.15)	(260.39)
fiveKshare:Weeks13-16	−0.01	−0.01	−0.06	−0.05	−0.06	−177.68
	(0.18)	(0.17)	(0.17)	(0.16)	(0.16)	(274.65)
fiveKshare:Weeks17-20	0.14	0.06	−0.03	0.02	−0.04	−629.56**
	(0.18)	(0.17)	(0.17)	(0.17)	(0.16)	(275.67)
fiveKshare:Weeks21-24	−0.47**	−0.53***	−0.60***	−0.57***	−0.61***	−360.13
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(288.07)
fiveKshare:Weeks25-28	−0.16	−0.24	−0.27	−0.32*	−0.30*	−105.58
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(285.69)
fiveKshare:Weeks29-32	−0.25	−0.16	−0.24	−0.26	−0.30*	−111.50
	(0.19)	(0.19)	(0.18)	(0.18)	(0.17)	(293.87)
fiveKshare:Weeks33-36	−0.005	0.06	−0.05	−0.05	−0.10	151.70
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(284.22)

(*continued on next page*)

Table 3 (*continued*)

	Dependent variable:					
	PercentChange (1)	PC_3avg (2)	PC_5avg (3)	PC_3max (4)	PC_5max (5)	HeadChange (6)
fiveKshare:Weeks37-40	−0.09	−0.02	−0.09	−0.05	−0.13	−24.81
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(285.71)
fiveKshare:Weeks41-44	−0.19	−0.08	−0.15	−0.08	−0.10	21.88
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(286.18)
fiveKshare:Weeks45-48	0.05	0.01	−0.05	−0.01	−0.05	57.19
	(0.19)	(0.18)	(0.18)	(0.17)	(0.17)	(283.79)
fiveKshare:Weeks49-52	−0.09	−0.15	−0.23	−0.24	−0.26*	−150.38
	(0.17)	(0.16)	(0.16)	(0.15)	(0.15)	(257.46)
Observations	208	208	208	208	208	208
R^2	0.58	0.67	0.67	0.63	0.65	0.52
Adjusted R^2	0.49	0.59	0.60	0.55	0.57	0.41
Residual Std. Error (df = 168)	10.37	9.89	9.77	9.38	9.23	15,652.94
F Statistic (df = 39; 168)	6.01***	8.75***	8.92***	7.47***	8.14***	4.71***

Note: Single (*), double (**), and triple (***) asterisks indicate statistical significance at the 10%, 5%, and 1% level, respectively.
Values in parenthesis are standard errors of estimated coefficients.

order to arrive at region-level insights, our work implements fed cattle slaughter as the key measure of industry performance. An important consideration is how the availability and price of various beef products were affected by changing sources of beef demand (i.e., food service to food retail) and how processing facilities of differing size were able to shift production to meet those changing trends. Chenarides, Manfredo, and Richards (2021) posit that resiliency in the food sector also revolves around the ability to switch between food service and retail distribution channels, and finds that firms better able to do so remain more viable during economic disruptions. Future research should expand on the relative flexibility (or inflexibility) of smaller facilities as data availability allows.

Additionally, to the extent new physical capacity remains dependent on labor (i.e., to operationalize it), then any human health risk will likely present challenges for the sector. This reflects the importance of the difference in physical and operational capacity, and highlights the flaw in designing policy to address physical capacity when supply of labor (and hence utilization rather than sheer existence of physical capacity) is the primary constraint. Further, we must consider how returns to scale at larger facilities may result in less reliance on labor per animal harvested and pound of meat produced. Unintended consequences (both for cost efficiency and human health) of a shift to be less dependent on larger processing facilities, and the higher labor relative to production that shift entails, must be considered when the source of industry stress is a human pandemic.

Finally, though isolated and quickly "resolved", statistical evidence does exist of slaughter disruptions being impacted by a region's reliance on large processing facilities. This finding begs the question—should substantial economic resources be allocated to improve industry performance during a "once-in-a-lifetime" event knowing that the industry (and others) rebounded within weeks? Carefully conducted cost-benefit analyses of governmental policy and potential industry restructuring is likely needed to better answer that question. Our refined investigation of production disruptions provides an important step to further inform and hopefully motivate that future research.

CRediT authorship contribution statement

Justin D. Bina: Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Glynn T. Tonsor:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Lee L. Schulz:** Conceptualization, Writing – original draft, Writing – review & editing. **William F. Hahn:** 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.

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Appendix A

Table A1
Descriptive Statistics for 2020 FI Slaughter, Presumed Operational Capacity, and Variables Explaining Cattle Harvesting.

		Region 5	**Region 6**	**Region 7**	**Region 8**
Weekly FI steer and heifer slaughter volume (head)	Mean	29,619	84,342	253,594	57,869
	SD	5155	10,024	34,503	8742
	Min	12,600	54,800	150,600	21,300
	Max	38,700	102,200	294,400	69,200
Weekly presumed operational capacity (head)	Mean	36,277	91,244	269,131	62,762
	SD	2479	6046	16,644	4152
	Min	28,200	73,900	216,700	48,500
	Max	40,700	100,500	291,000	68,500
PercentChange (%)	Mean	−3.0	−5.3	−2.5	−4.7
	SD	16.6	11.6	14.0	15.4
	Min	−58.8	−33.4	−48.0	−65.1
	Max	18.3	15.7	23.4	41.4
twoKshare (%)	Mean	52.4	20.8	28.2	60.5
	SD	4.0	1.5	1.9	4.3
	Min	46.4	18.8	26.0	55.2
	Max	67.0	25.6	34.9	77.9
fiveKshare (%)	Mean	0.0	59.5	60.4	43.2
	SD	0.0	4.2	4.0	3.1
	Min	0.0	53.7	55.7	39.4
	Max	0.0	73.1	74.8	55.7

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