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ARTICLE

Spatial price competition and buyer power in the U.S. beef packing industry

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Abstract

We develop a spatially-explicit model of the U.S. beef packing industry to study key questions related to competition in an oligopsony setting. Cattle supplies are modeled at the county level, and packing plants' location, capacity, and ownership are taken as given. Packers procure negotiated cattle by competing in prices in each local (county) market, while accounting for transportation costs and pre-existing contracted supplies (alternative marketing arrangements). The model, calibrated to match observed 2022 data, is solved for the Bertrand–Nash equilibrium prices. The computed markdown in the price packers pay for fed cattle is decomposed into three components: the portion due to the inherent spatial oligopsony power; the amount due to an aspect of market concentration (firms owning multiple plants); and the component due to contracting. We find that markdowns are moderate, about $3.69/cwt or 2.6% of the fed cattle price, on average. About 54% of this markdown is due to the spatial configuration of plants, 40% is due to pre-contracted supplies, and only 6% of the markdown is attributed to multi-plant ownership by firms. Separately from markdowns, capacity constraints are found to lower fed cattle prices by 0.8% on average. Beyond the baseline, simulated counterfactual scenarios highlight specific policy-relevant questions. Markdowns are reasonably robust across counterfactuals, decreasing only modestly when plants operate independently or the use of contracting is limited. Across all counterfactual scenarios, cattle prices per se are most affected by tightening capacity constraints (as arising from a major plant closure or an upward swing in the cattle cycle).

KEYWORDS
Bertrand–Nash equilibrium, buyer power, oligopsony, price discrimination, price markdown, procurement contracts

JEL CLASSIFICATION
L13, L66, Q13

1 | INTRODUCTION

The importance of oligopsony power has long been recognized as a key feature of agricultural markets, where production by a multitude of geographically dispersed farmers is channeled into a highly concentrated processing sector (Rogers & Sexton, 1994). The beef and cattle industry provides perhaps the most compelling example—the top four beef packing firms control about 85% of processing capacity (Crespi & MacDonald, 2022). The main concern here is that buyer power can result in noncompetitive markdowns on cattle prices paid to producers.[1] Indeed, market power in the U.S. meat processing industry has been a contentious issue for over a century, with the federal government first addressing the matter in the Packers and Stockyards Act of 1921. In the beef industry, the topic has received renewed scrutiny over the last decade as the spread between the wholesale beef prices received by packers and the fed cattle prices that packers pay to producers grew considerably after 2015 (Fischer et al., 2021). Concerns over market power in beef packing typically focus on packers' procurement of cattle and the potential exercise of oligopsony power (Bolotova, 2023; Garrido et al., 2022). Recent initiatives to promote competition in the American economy includes explicit attention to agricultural industries, with proposed policies aimed at supporting independent beef packers and bringing more transparency to cattle pricing (Andrew, 2022).

Technological change and the exploitation of economies of scale, along with complementary innovations in fed cattle procurement, have resulted in a dramatic reconfiguration of the U.S. meat packing industry over the last several decades, with most changes happening in the last two decades of the twentieth century (MacDonald et al., 2000; Ward, 2002). Fewer, much larger, and more efficient processing plants now operate in this industry, and the regional location of these plants has also evolved. The lower processing costs brought about by these changes have, ceteris paribus, benefited both producers and final consumers (MacDonald et al., 2023). Several studies probe whether and how this consolidation affected the exercise of market power in meatpacking. Schroeter's (1988) early analysis, with a conjectural-variation approach using aggregate data, finds modest price impacts. Azzam (1997) and Morrison Paul (2001) conclude that the anticompetitive effects of market consolidation in the beef packing industry are small in comparison to the cost efficiencies associated with consolidation. Using transaction-level data in an auction framework, however, Crespi and Sexton (2005) find more substantial markdowns in cattle prices, in the order of 5%–10%.[2]

A distinctive feature of the cattle and beef industry concerns the use of procurement contracts known as "alternative marketing arrangements" (AMAs). The prevalence of these procurement contracts has increased considerably over the last decades, and, at present, AMAs account for about 70% of cattle supplies. A somewhat unique aspect of these contracts is that they are typically settled based on spot market prices at or near the time of delivery (often, a USDA-AMS reported regional price). As it relates to market power, the main concern is that, having obtained a large portion of cattle via AMAs, beef packing firms may strategically underbid in the cash market thereby depressing

[1]The concept of "markdown" refers to the immediate manifestation of market power on the buyer side, whereby inputs of production are paid below the value of their marginal product (Syverson, 2024).
[2]See Wohlgenant (2013) for a comprehensive review of earlier work.

cattle prices (Garrido et al., 2022; Moschini & Smith, 2024; Xia & Sexton, 2004). Contracts such as AMAs also serve as powerful vertical coordination devices, however, with possibly large efficiency gains for all market participants (Crespi & Saitone, 2018; Koontz & Lawrence, 2010). Furthermore, suggestive empirical evidence indicates that the price impacts of AMAs may be small (Xia et al., 2019).

Two features appear unsatisfactory in most previous analyses of market power in the cattle and beef industry. First, the typical reliance on aggregate data has neglected the actual spatial configuration of the industry, an unsettling starting point when in fact, as suggested by Rogers and Sexton (1994), spatial considerations may be a key source of market power in agriculture. Second, the extent of market power is often assessed (implicitly or explicitly) vis-à-vis perfect competition.[3] A perfectly competitive benchmark is ill-defined, however, when in fact packing firms are highly concentrated, spatially differentiated, and operate under capacity constraints. Under such structural conditions, marginal-cost pricing cannot be an equilibrium outcome (e.g., Tirole, 1988, chapter 5). In other words, in this setting, beef packing firms are bound to possess some market power. Rather than attempting to "detect" the existence of market power, as done by many studies cited in the foregoing, we propose that a research objective with more immediate relevance is to characterize the nature of market power vis-à-vis the observed structural configuration of the industry. Accordingly, in this paper, we pursue a novel modeling strategy with the potential to provide insights into the exercise of oligopsony power in the beef packing industry.

The model we develop is consistent with key stylized facts of the industry. On the cattle supply side, it recognizes that fed cattle is the end result of a decentralized supply chain that involves several stages and typically lasts up to 2 years from calving (RTI, 2007). After completing the feedlot stage on a high-energy feed ration, the optimal timing to sell market-ready cattle comprises a narrow window (a few weeks). For all practical purposes, therefore, the short-run supply of fed cattle that matters for cash market transactions is very inelastic. Hence, our model assumes that the short-run supply of cattle is given. To characterize the spatial dispersion of cattle supplies, we use county-level data on fed cattle supplies from the 2022 U.S. Census of Agriculture. Given that the inelastic supply is converted into beef, in the short run this predetermined supply establishes the price of beef along the retail beef demand curve. How this beef price is transmitted to cattle prices depends, inter alia, on the processing sector which, as noted, involves few and large plants with a very concentrated ownership structure. To characterize the demand for the cattle input, therefore, we assemble specific plant-level information, from a variety of sources, concerning their actual location, operational capacity, and ownership.

Given the foregoing, therefore, one of the prominent features of the model we construct concerns the careful representation of the spatial configuration of the industry which, combined with non-trivial costs involved in the transportation of live cattle, gives rise to spatial differentiation in the transaction of fed cattle from producers to packers. Because of the inelastic supply of cattle, the model focuses on the price determination process in the short run. Similar to Garrido et al. (2022), we assume that plants compete in prices for the available fed cattle supplies in each local (county) market. Because of the imperfectly competitive structure, therefore, the equilibrium concept we use is that of Bertrand–Nash. This is a common approach in industrial organization research with differentiated products, and constitutes an obvious modeling first step in our setting because (a) the spatial configuration of the industry entails product differentiation (à la Hotelling); (b) the model is short-run in nature, taking firms' processing capacities as given[4]; and (c) it is descriptively in line with how the industry procures cattle in the negotiated (cash) market. Finally, the model accounts for the multi-plant ownership of large beef-packing firms, and for the fact that the

[3]For example, Lusk et al. (2021) and Azzam and Dhoubhadel (2022), argue that beef and cattle pricing during COVID-19-driven plant disruptions in the spring of 2020 were consistent with competitive outcomes.

[4]Following Kreps and Scheinkman (1983), for example, Cournot-type models are best viewed as relevant when competition involves long-run strategic variables (such as the choice of plant capacity), whereas Bertrand price model are more appropriate for capacity-constrained short run competition. See also Tirole (1988, chapter 5).

equilibrium in the cash market pertains to the actual available cattle supply. That is, the packing firm's objective is profit maximization, across all plants owned by the firm, while accounting for transportation costs and the existence of a given amount of supplies pre-committed to each plant via AMAs.

The model, calibrated to replicate observed 2022 data, can be solved to find the cattle equilibrium prices in all local markets. The computed equilibrium prices allow us to characterize market power by calculating average national and county-level markdowns on fed cattle prices. We also provide a novel decomposition of these markdowns into three components: one due to the spatial differentiation of the industry; one due to an aspect of market concentration (firms' ownership of multiple plants); and, the final one due to the presence of pre-committed, AMA-contracted supplies. The baseline model suggests that markdowns in the industry, under the postulated Bertrand–Nash mode of competition, would be moderate—we find \$3.69/cwt or about 2.6% of the fed cattle price, on average. About 54% of the markdown is due to the spatial configuration of plants, 40% is due to contracting, and only 6% of the markdown is attributed to multi-plant ownership by firms.

Separately from markdowns, we also characterize the impact of capacity constraints on fed cattle prices. The importance of capacity constraints in determining fed cattle prices has been acknowledged in previous work (Azzam & Dhoubhadel, 2022; Bina et al., 2022; MacDonald, 2024; Peel, 2021), albeit without a model to quantify their implications. We use the approach of Ryan (2012) and Miller and Osborne (2014) to flexibly incorporate capacity constraints into the structural model. We find that the existence of capacity constraints further lowers fed cattle prices, beyond the Bertrand–Nash markdown, by about \$1.16/cwt in the baseline model.

To fully appreciate the insights from the proposed approach, we use the model to simulate several counterfactual scenarios. We analyze six policy-relevant scenarios: (a) an exogenous increase in fed cattle supplies; (b) an exogenous decrease in fed cattle supplies; (c) each plant operating independently; (d) a limit on the maximum use of AMAs in the industry; (e) the entry of a mid-sized new plant; and (f) the exit of a large existing plant. We find that the prices move in the expected direction in each scenario. Changes in cattle supply, mimicking the magnitude of the cattle cycle, have large impacts on cattle prices, but minor impacts on markdowns. Markdowns decrease by 23% in the independent plant scenario and 15% in the limited contracting scenario. However, because the markdown is small relative to the fed cattle price in the baseline, these changes lead to only small increases (around 1%) in fed cattle prices. Plant entry and exit have relatively small impacts on prices, and most of the price change in these scenarios is due to the easing or tightening of capacity constraints.

Given the nature of the analysis we present, some caveats apply. First, the model of competition takes cattle supplies as given, and thus it has little to say about the welfare impact of the exercise of market power (beyond the redistribution of profit between farmers and packers implied by price markdowns). Also, the model we parameterize and apply to compute industry equilibria inevitably relies on assumptions that are difficult to validate vis-à-vis the available data. Still, within the economic environment that we model, the analysis highlights and evaluates the role of various critical structural elements of the industry. In particular, we assess how specific industry attributes—such as the spatial configuration of the industry, firms' ownership of multiple plants, the widespread use of procurement contracts, and the existence of capacity constraints—are expected to affect price markdowns. Insofar as the predictions of the model fail to reasonably match observed data, the likely explanation may be sought in features omitted from the current model. In particular, we note that our model proceeds with the standard Bertrand–Nash formulation. We have argued explicitly that this equilibrium concept is natural in the context of the industry we model. Other, more nuanced conduct hypotheses may better match observed market outcomes, however, including the possibility of collusive behavior. Exploration of such challenging questions is left for future research.

2 | THE CATTLE-BEEF INDUSTRY: A BRIEF BACKGROUND

Before proceeding to the data and modeling, a brief background on the cattle industry is useful for understanding some aspects of the model. The information in this section is largely drawn from the descriptions of the industry from reports by RTI (2007) and the U.S. Government Accountability Office (2018). The supply chain for beef is an 18–24 month process that begins with calves being born on cow-calf operations, typically in the spring. Calves stay with the cows grazing pasture throughout the summer and fall, before being weaned at a weight of 400–600 pounds and being placed in preconditioning lots, backgrounding lots, or winter pasture systems. After the winter, the cattle weigh 600–800 pounds and are sent to the next stage, which varies based on their size. Smaller animals, known as stocker cattle, are placed in summer pasture, while larger animals, known as feeder cattle, are placed into feedlots. The stocker cattle are placed into feedlots as feeder cattle in the fall.

Feeder cattle spend 4–6 months in the feedlot being fed a high-energy ration that supports the growth of heavy muscle and fat suitable for beef production. When they reach a weight of 1150–1350 pounds, they are marketed to beef packers as fed cattle. Packers purchase the fed cattle either through direct negotiation on the spot market or through AMAs.

The basis for fed cattle pricing in the negotiated (cash) market can be categorized along two axes: live or dressed weight; and free on board (FOB) or delivered pricing (USDA-AMS, 2020; USDA-GISPA, 2014).[5] Live weight refers to the weight of the animal at the feedlot, prior to transportation to the packing plant. Dressed weight refers to the weight of the "hot carcass" at the packing plant after slaughter and removal of byproducts. Cattle typically have a dressing percentage—the ratio of dressed weight to live weight—of around 63%. FOB pricing occurs when the packer pays for transportation, while delivered pricing refers to the feedlot paying for transportation. Together, these two axes form a two-by-two matrix of pricing bases: live FOB; live delivered; dressed FOB; and dressed delivered. Of these, the most common pricing basis is live FOB, followed by dressed delivered.

An additional wrinkle in determining the pay weight of live cattle—the amount of weight paid for by the packer—is the desire to account for the weight lost by cattle during transport from the feedlot to the packer. Packers account for this weight loss by factoring in a "pencil shrink" in their procurement arrangements (USDA-GISPA, 2014, p. 9), by which they reduce the feedlot-gate weight of the cattle by an appropriate amount to reach the final pay weight.[6]

Whereas the negotiated market is critical for price discovery in the industry (Bastian et al., 2021), the majority of fed cattle are now procured via AMA contracts with base prices pegged to market outcomes to be determined at a later date. These arrangements include formula purchases, whose base price is tied to the cash market price, and forward contracts, whose base price is tied to the futures market. Formula purchases are much more common than forward contracts, accounting for nearly 90% of these arrangements in 2022. The base price for formula purchases is typically taken from a weekly USDA report on negotiated cattle prices.[7]

The transportation of fed cattle is costly, both in monetary terms and in the potential for lost value (Coffey et al., 2001). In addition to the weight lost to shrink, cattle may be bruised or maimed during transport (NBQA, 2022). Once cattle arrive at the packing plant, they are slaughtered and

[5]This use of the term "FOB" in USDA's cattle price reporting, essentially referring to prices at the farm, has a somewhat different interpretation than commonly used when describing price policies by buyers in an oligopsony market (e.g., Graubner et al., 2021).

[6]Negotiated prices often involve a grid specifying premiums and discounts, relative to the base price, based on quality. Indeed, the need for incentives to ensure the desired level of quality in the supply chain is one of the recognized factors impacting the diffusion of contracting in many agricultural markets. For reasons similar to those articulated by Xia and Sexton (2004, p. 126), however, such considerations are omitted from our model because our central objective is to characterize the extent of market power as reflected in the equilibrium base prices.

[7]The Cattle Contracts Library Pilot Program (https://www.ams.usda.gov/market-news/livestock-poultry-grain/cattle-contracts-library) has details on the reports used for base prices, and some of the premiums and discounts applied in the contracts. An additional feature of AMAs is that, as recognized by Schroeter and Azzam (2004), feedlot operators typically retain some discretion as to the actual delivery time of the contracted supply. This element, in any case, does not come into play in the model below, which is calibrated to annual data.

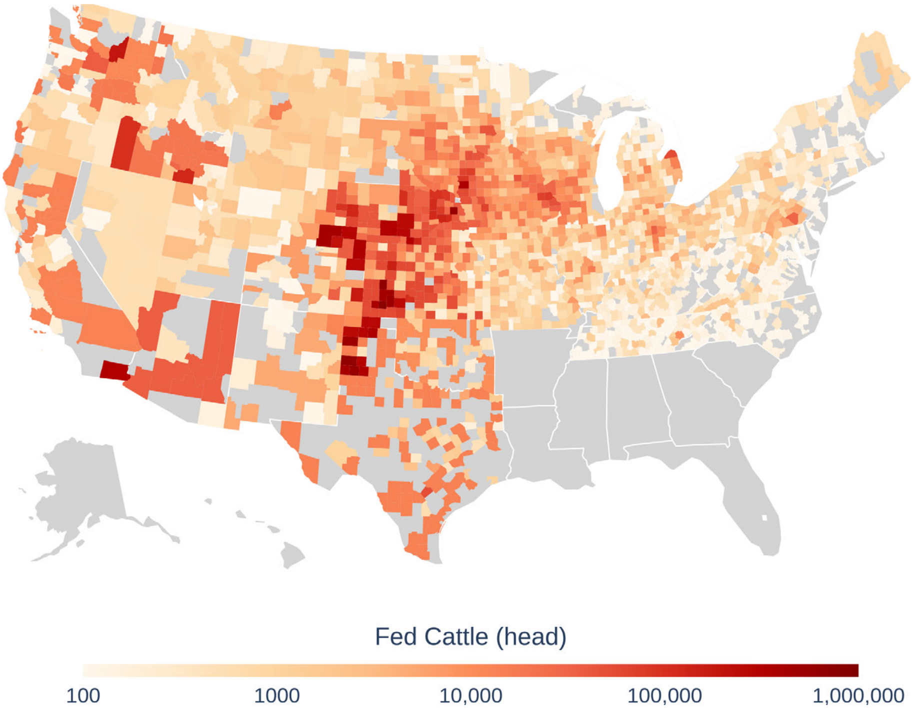

FIGURE 1 County-level fed cattle supplies in 2022. The map shows estimated county-level fed cattle supplies in 2022. Gray areas have zero fed cattle sales in the most recent Census of Agriculture. *Source*: Data are from the 2022 USDA Census of Agriculture Cattle On Feed—Sales for Slaughter.

processed into primal cuts of beef that are vacuum sealed, boxed, and sold to wholesalers as boxed beef. The packing plants typically run single shifts 5 days per week, with an additional Saturday shift acting as a "shock absorber" for excess supply (Bina et al., 2022).

Thousands of cow-calf operations, backgrounding lots, and feedlots operate in the United States, but just four beef packing firms operating 23 plants account for 83% of the nation's capacity to process fed cattle into boxed beef. Discussions of market power in the industry therefore primarily focus on the conduct of the packing firms, especially in their procurement of fed cattle from feedlots.

3 | DATA

We collect data on county-level fed cattle sales from the 2022 USDA Census of Agriculture, the most recent year in which census data is available. It turns out that the sales volumes for some counties are redacted for confidentiality reasons.[8] In fact, redacted counties account for a sizeable portion of total cattle sales (around 23% of the national total). Because excluding such a large portion of supply would distort the analysis, we use the corresponding state-level sales number to impute each redacted county a value such that the county totals within each state add up to the correct value. Specifically, using the available Census data, for each state we find the total redacted volume by taking the difference between the state-level sales total and the sum of county-level sales of unredacted counties. The total redacted sales volume of the state is then allocated evenly across the redacted

[8]The specific data we use pertain to "Cattle on feed—Sales for slaughter, measured in head." As stated in the Census documentation, for some counties such data entries are "Withheld from publication to avoid disclosing data for individual farms."

TABLE 1 Estimated beef packer summary statistics for 2022.

		Estimated capacity	
Firm	**Number of plants**	**Average (per plant)**	**Total**
JBS	8	3144	25,150
Tyson	6	4600	27,600
Cargill	6	3700	22,200
National Beef	3	4400	13,200
Other	20	921	18,415
Total	43	2478	106,565

Note: This table shows summary statistics for the 43 beef packing plants that process fed cattle in our dataset. Average capacity and total capacity figures are in units of head per day. Based on data from *Cattle Buyers Weekly*, USDA FSIS, and various market and news reports.

counties in the state. The census reports a total of 24.4 million head of cattle sold for slaughter in 2022. About 77% of the total sales for slaughter come from the top five cattle producing states of Kansas, Nebraska, Texas, Colorado, and Iowa. Figure 1 shows the spatial distribution of fed cattle supplies.[9]

Data on the capacities and locations of beef packing plants are assembled from a variety of sources (see the Supporting Information Appendix, Part I, for more details). We begin with data from *Cattle Buyers Weekly* (CBW) on the 30 largest U.S. beef packing firms in 2022. This report includes data on firm-wide capacity, measured in head per day, total firm-wide slaughter, and the percentage of fed cattle (as opposed to culled cows and bulls) in each firm's total slaughter. These top 30 firms operate 54 plants, of which 43 process at least some fed cattle. The firm-wide slaughter data indicate that these 30 firms accounted for at least 90% of U.S. federally inspected fed cattle slaughter in 2022.[10] We supplement the firm-level CBW data with the Meat, Poultry and Egg Product Inspection Directory from the USDA Food Safety and Inspection Service (FSIS). The plant-level FSIS data include ownership information, allowing us to match specific plants with the firms in CBW data, and plant addresses, allowing us to precisely locate plants in space.

We disaggregate the firm-level CBW capacity data with various news and market reports that mention plant's individual processing capacities. We combine these reports with the CBW data on firm-level capacity and fed cattle percentage to produce our best judgment of each plant's capacity for processing fed cattle. This capacity value is a measure of daily physical capacity, which we multiply by 240 to get the plant's annual operational capacity. See the Supporting Information Appendix, Part I, for more details on this adjustment. The end result is a dataset comprising the ownership, spatial configuration, and capacity of the major plants accounting for the vast majority of U.S. fed cattle processing. Table 1 reports their summary statistics. These estimated capacity figures confirm the high concentration level of this industry: the 23 plants of the four largest firms account for about 83% of the industry capacity.

Figure 2 shows the size and spatial distribution of the packing plants in the data set. Comparing Figures 1 and 2, we can see beef processing capacity is clustered in areas with high concentrations of fed cattle supplies. In addition to producing 77% of the nation's fed cattle, the five states of Nebraska, Kansas, Texas, Iowa, and Colorado also contain 77% of U.S. beef processing capacity. This clustering occurs because of the high costs of shipping live cattle compared to shipping boxed beef, and supports our model's presumption that the spatial configuration of cattle and plants plays a key role in determining market outcomes.

[9]The main differences between Figure 1 in the text and fig. B.1 in Garrido et al. (2022), beyond the fact that we use the most recent Census of Agriculture data, is that in Figure 1 we account for the sales volumes redacted by the USDA.

[10]These data are available to CBW subscribers, see the CBW website for further details: https://cattlebuyerweekly.com/. CBW does not report slaughter figures for some firms, suggesting that the top 30 firms actually accounted for even more than 90% of federally inspected slaughter.

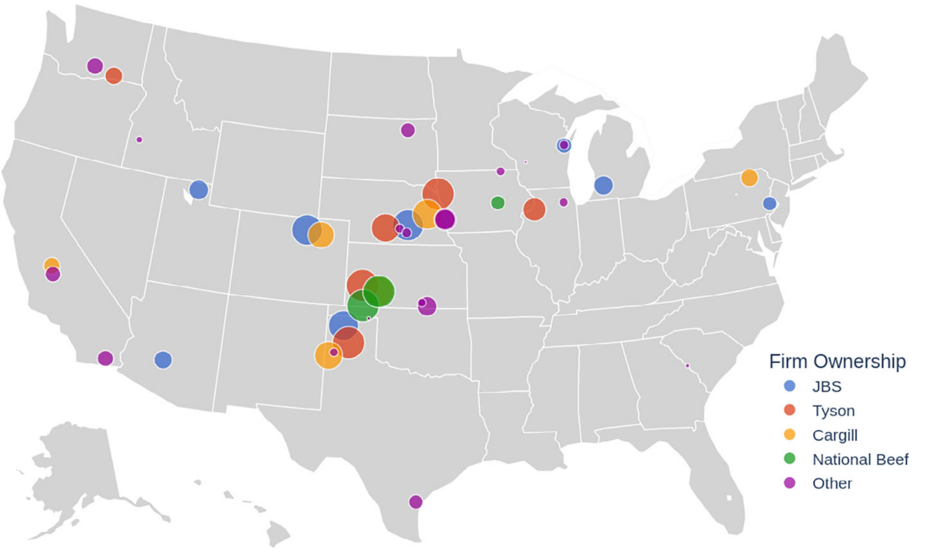

FIGURE 2 U.S. beef packing plants 2022. The map shows the location of U.S. beef packing plants in 2022. Circle size is proportional to plant capacity, and color represents the firm ownership of the plant. *Source*: Based on data from *Cattle Buyers Weekly*, USDA FSIS, and various market and news reports.

4 | MODELING FRAMEWORK

We develop a model of price determination in the fed cattle market that incorporates key spatial aspects of the industry and is suitable for calibration and computation of equilibria. The framework is that of a static, one-period model of oligopsony competition among the packing firms. The location of fed cattle supplies and the location and capacity of beef packing plants are taken as given. The supply quantity of cattle to be slaughtered is also assumed as fixed. As noted earlier, cattle supply is the result of a lengthy process that spans several years. The price determination process, on the other hand, is very much a short-run process, where cattle procurement by packing plants follows a weekly cycle. The quantity of cattle nearing optimal marketing weight is the result of feedlot stocking and calving decisions taken months or years earlier. Feedlot operators have a narrow window to market their cattle, spanning at most 2 or 3 weeks. Accordingly, and more so because we calibrate the model to match annual data, we assume that the cattle supply is perfectly inelastic.

We focus squarely on the issue of buyer power affecting the transaction of fed cattle from producers to packers, and thus assume that packers sell the beef they produce at an exogenously given price. Given a fixed quantity of processed cattle, and noting that the transformation of cattle into beef involves essentially fixed proportions, the retail beef price is presumably determined by final consumers' demand. Hence, exogeneity of the retail beef price appears a natural assumption given that the supply of cattle is perfectly inelastic. How retail price translates into a wholesale price of beef, of course, may depend on the relative bargaining power of retailers vs. beef packers, an issue that we do not address in this paper.

In the model, cattle are treated as a homogeneous good, but the spatial component of supply and processing activities makes this a setting of differentiated products (à la Hotelling). Hence, we essentially model price determination in a Bertrand–Nash oligopsony framework for differentiated products. Other elements of differentiation in the cattle and beef industry, mostly related to quality issues (Peel, 2021), are not directly addressed.

Our model is along the lines sketched out in Garrido et al. (2022), but we take a more direct computational approach. We believe that the complexities of the multi-year cattle supply cycle, the subtle role of contracting relations, and the un-observability of critical data make econometric estimation of a full equilibrium model for the cattle and beef industry exceedingly challenging. For the purposes of this paper, therefore, our strategy is to specify a model capable of capturing the salient features of the industry, with emphasis on its spatial configuration, calibrate its parameters to fit known stylized facts, and use the model to solve for a baseline equilibrium and several counterfactual scenarios.

4.1 | Cattle supplies and market shares

The model we develop is one of price competition. Each beef packing firm $f \in \mathcal{F}$ owns a set of plants $\mathcal{J}_f$, with a total of J plants operating in the market. Firms procure cattle for all their plants by competing in price in each local market. That is, plant j purchases fed cattle in the spot market in county $n = 1, 2, \ldots, N$ by offering price p_{jn}. Furthermore, as noted earlier, procurement agents' bids typically quote both a nominal price and a standard "pencil shrink" factor, denoted σ_{jn}, meant to account for the cattle weight shrink due to transportation.[11] Thus, in units of farm-gate weight, the price received by the producer is $p_{jn}\left[1-\sigma_{jn}\right]$. We assume that the pencil-shrink factor, $\sigma_{jn} = \sigma\left(d_{jn}\right)$, is directly related to the distance d_{jn} from county n to plant j. Thus, the strategic variables for the packing firms are assumed to be the bid prices.

Having accounted for the pencil shrink factor, we write the value of selling to plant j for producer i located in county n as:

$$V_{ijn} = \alpha p_{jn}\left[1-\sigma_{jn}\right] + \varepsilon_{ijn}. \tag{1}$$

It may not be obvious why this formulation is appropriate. A more immediate representation would be the special case of $\alpha = 1$ and $\varepsilon_{ijn} = 0$, such that producers simply sell to the highest (net) price offer. The characterization of equilibrium under such condition would be problematic, however. Even without the spatial dimension, characterization of price competition equilibria under capacity constraints is non-trivial and may require mixed strategies. For computational purposes (and economic interpretation), however, it is highly desirable to work with pure strategies. Imposing $\alpha = 1$ and $\varepsilon_{ijn} = 0$ would implictly assume that, in a pure-strategy equilibrium, the entire supply of a county would accrue to just one plant (recall that our cattle supply data is at the county level, not at the individual level), which is unattractive.

Whereas the representation in Equation (1) is best viewed as a convenient parameterization of a canonical spatial equilibrium framework where feedlot operators just choose the best price, a more literal interpretation is also possible. The term ε_{ijn} captures the producer's unobserved idiosyncratic preference for selling to plant j, due to factors such as a long-lasting relationship with the buyer, or perhaps a desire to work with larger or smaller firms. The parameter α is a scaling factor that captures the producer's sensitivity to price as compared to their unobserved preference.

Further assuming that the unobserved preferences have a Type 1 Extreme Value (T1EV) distribution (Train, 2009), and integrating over all fed cattle producers in the county, allows us to derive plant j's market share in county n as:

[11] Our formulation is consistent with industry practices whereby cattle procurement bids for negotiated sales typically feature both a nominal offer price and a pencil-shrink factor (USDA-GISPA, 2014). Still, the desirability of such a parameter in the model is perhaps a moot point, as what matters to both sellers and buyers is, essentially, the net price. Because the shrink factor interacts somewhat with how the model handles transportation costs and the final slaughter weight, however, we choose to maintain it explicitly in the parameterization model. Solution for the special case $\sigma_{jn} = 0$, of course, is readily possible.

$$s_{jn}(\mathbf{p}_n) = \frac{\exp\left(\alpha p_{jn}\left[1-\sigma_{jn}\right]\right)}{\sum_{k=1}^{J}\exp\left(\alpha p_{kn}\left[1-\sigma_{kn}\right]\right)}, \tag{2}$$

where $\mathbf{p}_n \equiv [\, p_{1n}, p_{2n}, \ldots, p_{Jn}]'$ is the vector of plant-specific prices in the county. Note that, as the parameter α gets larger, the share of the plant with the largest price approaches one and the shares of plants with lower prices go to zero.[12]

4.2 | Packing plants and firms

Firms procure cattle for all their plants by competing in price in each local market. In addition to these spot market transactions, the model maintains that a portion of cattle supplies are pre-committed to buyers via AMA contracts. Specifically, we assume that each plant has a pre-committed quantity of cattle $\overline{x}_{jn}$ from county n via contracts. The total supply of fed cattle in county n is denoted Q_n, and the quantity of cattle available on the spot market is $M_n \equiv Q_n - \sum_j \overline{x}_{jn}$. The amount of cattle procured on the spot market by plant j in market n, therefore, can be written as $s_{jn}(\mathbf{p}_n)M_n$.

Consistent with the main distinguishing feature of procurement contracts in this industry, contracts are settled at the average regional spot market price $\overline{p}_r$, with regions defined by those used in the USDA Livestock Mandatory Reporting (see the Supporting Information Appendix, Part II, for more details on these regions). For all counties in region r, the average spot market price is given by:

$$\overline{p}_r(\mathbf{p}) = \sum_{m\in r}\left[\frac{M_m}{\sum\limits_{\ell\in r} M_\ell}\sum_{j=1}^{J} s_{jm}(\mathbf{p}_m)p_{jm}\right], \tag{3}$$

where $\mathbf{p}$ denotes the vector of all prices across all counties.

Packing plant j ships the cattle it purchases from the county to the plant at a cost $t_{jn} = t\left(d_{jn}\right)$ per unit of cattle. Cattle are processed into beef in fixed proportions. The total variable cost function at the plant level, presumed increasing and convex in the quantity processed at the plant, is denoted $C\left(q_j(\mathbf{p})\right)$, where $q_j(\mathbf{p}) = \sum_{n=1}^{N}\left[s_{jn}(\mathbf{p}_n)M_n + \overline{x}_{jn}\right]$ is the total number of cattle processed at plant j.[13] Packers sell the resulting beef on the wholesale market for price b which, as noted, they take as given. With this setup, the profits of firm f, from all of its packing plants, are given by:

$$\Pi_f(\mathbf{p}) = \sum_{k\in\mathcal{J}_f}\left[\sum_{n=1}^{N}\left[s_{kn}(\mathbf{p}_n)M_n\left(b - t_{kn} - p_{kn}\right) + \overline{x}_{kn}\left(b - t_{kn} - \overline{p}_r(\mathbf{p})\right)\right] - C\left(q_k(\mathbf{p})\right)\right]. \tag{4}$$

Our formulation is similar to that of Garrido et al. (2022), though these authors assume that the feedlots, rather than the packers, pay for transportation costs. Our formulation is a direct representation of the live FOB pricing method that is most common in the industry, while the formulation of Garrido et al. (2022) is perhaps best interpreted as dressed delivered pricing. In any event, the important assumption here is that firms compete head-to-head, with plant-specific prices, in each local market. Who pays for transportation costs is immaterial. Specifically, if one assumes that

[12]An alternative rationalization of the logit representation of Equation (2) arises from an auction framework (Crespi & Sexton, 2005), whereby $s_{jn}(\mathbf{p}_n)$ can be interpreted as the probability of plant j acquiring the cattle supply in county n, given the vector of plants' price bids $\mathbf{p}_n$.

[13]Variable processing costs include wages for workers, energy consumption, and maintenance of the packing plant's equipment and facility. Processing plants also have (possibly large) fixed costs, related to facility establishment and the acquisition of equipment, and other overhead costs. Insofar as these costs are not relevant for the characterization of the short-run equilibrium of interest, they can be ignored.

(a) transportation is provided by a competitive industry at a price that feedlots and packers take as given, and (b) the dressing percentage of the fed cattle is constant, then the distinction between these pricing methods does not matter.

We model variable costs being mindful that capacity constraints are an important feature of the processing plants. Adapting the parametric representation of Ryan (2012) and Miller and Osborne (2014), we assume that plants have an "operational capacity" K_j which may be exceeded only with (sharply) increasing marginal cost. In particular, we specify the plant-level marginal cost function, defined as $c(q) \equiv \partial C(q)/\partial q$, as:

$$c\left(q_j(\mathbf{p})\right) = c_0 + \mathbf{1}\left\{q_j(\mathbf{p}) > K_j\right\} \times \gamma \left(\frac{q_j(\mathbf{p})}{K_j} - 1\right)^{\lambda}, \tag{5}$$

where c_0 is the base marginal cost, $\mathbf{1}\left\{q_j > K_j\right\}$ is an indicator function that takes value 1 if the condition in braces is true (0 otherwise); and γ and λ are parameters that govern the steepness of the cost increase that occurs when production exceeds the operational capacity.[14]

4.3 | Bertrand–Nash price equilibrium

The foregoing representation of cattle procurement by packing firms maintains what, in industrial organization, is known as the price-discrimination strategy. Alternatively, one could postulate that plants compete by setting mill prices (uniform plant-level prices), with the net price accruing to producers determined in conjunction with (exogenous) transportation costs. Either pricing strategy could be appropriate, in principle, but the price-discrimination setup appears a closer representation of business practices in the cattle procurement setting (RTI, 2007). Also, Thisse and Vives (1988) show that the price discrimination strategy emerges as a unique equilibrium outcome in games where firms choose both the pricing policy and prices themselves.

Packing firms maximize their profits from the set of all plants they own, as given by Equation (4), by optimally setting the plant-specific prices they offer to cattle producers in each county. When the objective function includes quantity-dependent marginal costs, some care may be necessary (e.g., Conlon & Gortmaker, 2020, pp. 1152–1153). The optimality conditions for the profit maximization problems of packing firms can nonetheless be characterized in terms of the marginal cost function, as follows (see Appendix A for details):

$$M_n\left[-s_{jn}(\mathbf{p}_n) + \sum_{k \in \mathcal{J}_f} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}\left(b - c\left(q_k(\mathbf{p})\right) - t_{kn} - p_{kn}\right)\right] - \frac{\partial \overline{p}_r(\mathbf{p})}{\partial p_{jn}} \sum_{\ell \in r} \sum_{k \in \mathcal{J}_f} \overline{x}_{k\ell} = 0 \tag{6}$$

The $J \times N$ equations in (6) define the set of best response functions which characterize the full set of equilibrium prices p_{jn}^*, where $j = 1, \ldots, J$ and $n = 1, \ldots, N$.

4.4 | Model calibration

We calibrate the model to the calendar year 2022 data, the most recent year for which we have full market data. As described previously, we start by assembling data on fed cattle supplies and the

[14]As mentioned in the Introduction, economies of scale are often cited as a major explanation for the development of larger plants and the reconfiguration of the beef packing industry that took place in the last decades of the twentieth century. We note at this juncture that the specification in (5) is consistent with economies of scale playing a role in the model. Specifically, constant marginal costs are sustainable over a wider output range for large plants (i.e., average costs are decreasing at least up to K_j, which is higher for larger plants).

TABLE 2 Model parameter calibrations.

Variable	Definition	Calibrated value	Units
α	Producer price sensitivity	56.28	
b	Wholesale beef price	3.977	\$/lb
c_0	Base marginal cost	0.3608	\$/lb
γ	Marginal cost coefficient above threshold	2.1785	\$/lb
λ	Marginal cost curvature above threshold	1.5	
$t(d_{jn})$	Per-unit transportation cost function	$\frac{4.0583\times10^{-4}\times d_{jn}}{1-\sigma(d_{jn})}$	\$/lb, d_{jn} in miles
$\sigma(d_{jn})$	Shrink factor function	$0.01+2.5\times10^{-4}\times\min\{d_{jn},100\}$	d_{jn} in miles

Note: This table presents key information on the calibrated parameters of the model. Values for some parameters are typically discussed in terms of other units, such as \$/head or \$/loaded mile. We convert and present all parameters in units of \$/lb of beef to ensure consistency throughout the model. Note that the calibration of the α coefficient is conditional on the variance of the T1EV distribution, which we assumed to be the standard $\pi^2/6$.

capacities and locations of packing plants in 2022. We then calibrate the parameters of the model using publicly available information, and conversations with industry professionals where such sources are relevant. Finally, we calibrate unobservable parameters so that model outcomes match observable variables. The calibrated parameters are reported in Table 2.

The wholesale beef price b, in units of dollars per pound of retail beef, is taken from USDA ERS data on meat price spreads.[15] The transportation cost function is derived from the implied fed cattle hauling rates calculated by Dennis (2023). Because the implied hauling rate for 2022 appears to be somewhat of an outlier (about 70% higher than any previous rate), we use the average of the rates over 2021–2023. We assume that this average implied hauling rate of \$2.57/cwt applies to fed cattle that travel the national average hauling distance of 152 miles (NBQA, 2022), and we convert the value into units of dollars per pound of retail beef to ensure consistency throughout the model.[16] When reporting our results in later sections, we convert prices and markdowns into units of \$/cwt (dollars per hundred pounds of live weight) for consistency with how these prices are usually reported.

The marginal cost curvature parameters λ is set to 1.5, as in Miller and Osborne (2014). We then calibrate the marginal cost coefficient γ such that the marginal cost for a plant operating at 20% over operational capacity increases by 50% over the baseline marginal cost c_0. Note that, if we interpret nameplate capacity as plant utilization for a 5-day week operation (Monday to Friday, as standard in the industry), a 20% over-capacity utilization correspond to a full Saturday shift. Similarly, the parameterization implies that a half-day Saturday shift increases marginal processing costs by 18%. This is illustrated in Figure 3.

The shrink factor function $\sigma(d_{jn})$ is calibrated based on Falkner (1998), who shows that the majority of shrink generally occurs during the loading process and the first 100 miles of transport. We assume that cattle shrink by 1% while being loaded for transportation, shrink at a rate of 0.025% per mile for the first 100 miles of transport, and do not shrink further when traveling over 100 miles. Cattle therefore shrink by a maximum of 3.5% during transport, which occurs on a trip of 100 miles or more.

We calibrate cattle producers' price sensitivity α and the base marginal cost c_0 based on the model's fit with two key observable outcomes: average fed cattle price, and average procurement distance from feedlot to packing plant. ERS Meat Price Spreads data reports an average fed cattle price of \$142.66 in 2022, and the 2022 National Beef Quality Audit (NBQA, 2022) reports that fed cattle travel an average of 152 miles to the slaughter facility. After calibrating all other parameters as

[15]See https://www.ers.usda.gov/data-products/meat-price-spreads/.

[16]We assume an average yield 0.417 pounds of retail beef per pound of live weight at the plant gate.

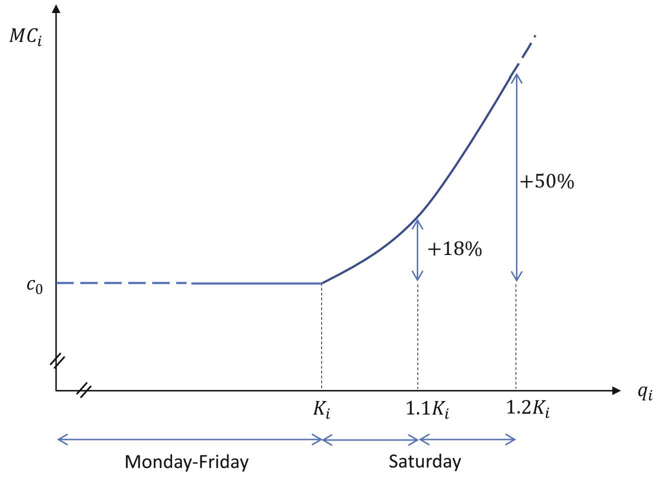

FIGURE 3 Marginal processing costs and capacity constraints. This figure illustrates the shape of plant-level processing costs. The plant's nameplate capacity K_i is assumed to correspond to a 5-day/week operation. A full Saturday shift, corresponding to a 20% increase in throughput relative to the 5-day week, is assumed to entail a 50% increase in marginal processing costs.

described above, we jointly adjust α and c_0 until the model equilibrium reflects these values. This results in a value for α of 56.28 and a value for c_0 of 0.3608 dollars per pound of retail beef. Notably, this value of c_0 aligns well with processing costs reported in CanFax (2010) and Newlin (2020).

To calibrate the pre-committed supplies $\overline{x}_{jn}$, we first compute the Bertrand–Nash equilibrium of the industry under the assumption of no contracting. This results in a set of plant-county-level market shares, $\overline{s}_{jn}$, $j = 1,\ldots,J$ and $n = 1,\ldots,N$. Thus, in this equilibrium, the quantity of cattle procured by plant j from county n is equal to $\overline{s}_{jn}Q_n$. We assume a fixed portion of this quantity will be pre-committed supplies in the baseline equilibrium. That is, we assume $\overline{x}_{jn} = \varphi_r \overline{s}_{jn} Q_n$, where φ_r is the regional contracting share discussed in the Supporting Information Appendix, Part II.

4.5 | Computation of equilibria

Given the model parameterized as described above, we compute the set of Bertrand–Nash equilibrium prices p^*_{jn}, where $j = 1,2,\ldots,J$ denotes plants and $n = 1,\ldots,N$ denotes counties. The model explicitly considers 43 plants, owned by 22 firms, with cattle supplies coming from 1993 counties in 39 states. In principle, the model can allow any one plant to bid for cattle in all counties. Realistically, however, the logistics of transporting live animals puts constraints on our far plants can go to procure cattle. In computing equilibria, therefore, we assume that plants do not compete for cattle in counties that are more than 650 miles away from the plant location, with distances measured from the plant to the county centroid. With this distance assumption, we end up solving for 34,669 plant-county-level equilibrium prices. This is done by solving the system of equations in (6) via a fixed-point procedure akin to that of Morrow and Skerlos (2011). Specifically, the algorithm presented in Morrow and Skerlos (2011) applies to a product-differentiated oligopoly, which we adapt for use in our oligopsony setting.[17] See Appendix B for details.

[17]Conlon and Gortmaker (2020), and Luo et al. (2023), report of the superiority of this procedure relative to the standard fixed-point algorithm common in industrial organization (e.g., Nevo, 2001).

5 | BASELINE EQUILIBRIUM

With the model calibrated to match observed 2022 data, we first consider the properties of the baseline equilibrium solution. The model yields equilibrium price bids and market shares for each of the 1993 local markets (counties) that we consider, which can then be aggregated regionally and nationally. One of our main initial objectives is to quantify the price markdown in the modeled fed cattle procurement market. Furthermore, we show how this markdown can be decomposed into three portions: one portion due to contracting; one portion due to firms' ownership of multiple plants; and the final one due to the spatial configuration of plants. We also quantify the price effects of capacity constraints in the model.

5.1 | Prices and markdowns

The price "markdown" in our oligopsony setting identifies the extent by which fed cattle, as an input of production in beef-packing, is paid less than its marginal value product. To characterize this concept as it applies to our model, we start by defining four sets of prices. First, the baseline equilibrium prices p_{jn}^* are the plant- and county-specific prices obtained from the Bertrand–Nash equilibrium with the observed configuration of plant ownership and contracting, as articulated in section 4. The equilibrium price configuration also defines the set of plant-level processing activities $q_j(\mathbf{p}^*)$. In turn, these plant-level quantities imply the baseline equilibrium marginal costs for each plant j, that is, $c\left(q_j(\mathbf{p}^*)\right)$. In the computations that follow, we maintain each plant's marginal cost at this equilibrium level for internal consistency in decomposing the markdown.

The second set of prices needed for the markdown decomposition are "no-contract" prices, p_{jn}^{nc}. These are found by computing the Bertrand–Nash equilibrium of the market as described above, but with all AMA contracted volumes set to zero (i.e., $\overline{x}_{jn} = 0,\ j = 1,\dots,J; n = 1,\dots,N$). Next, we find the set of "independent" prices, p_{jn}^{ind}, by further adding the assumption that each plant maximizes its own profit independently (that is, we assume both no contracting in the market and independent plants). Finally, we find the set of marginal "breakeven prices," denoted p_{jn}^{be}. These prices are county- and plant-specific: plant j's breakeven price in county n corresponds to the maximum price that plant j could offer—from the perspective of the computed equilibrium—on another head of cattle from county n. Note that this notion identifies the marginal value product of the input, such that the marginal breakeven price is defined as $p_{jn}^{be} = b - c\left(q_j(\mathbf{p}^*)\right) - t_{jn}$.

Given the foregoing, the total markdown by plant j in county n observed in equilibrium is:

$$\mu_{jn} \equiv p_{jn}^{be} - p_{jn}^*. \tag{7}$$

Again, the markdown is the difference between the highest price that plant j could pay fed cattle in county n, given its location and equilibrium marginal costs, and the price it actually pays. We can then decompose this value into three components:

$$\mu_{jn} = \underbrace{\left(p_{jn}^{be} - p_{jn}^{ind}\right)}_{\mu_{jn}^{spatial}} + \underbrace{\left(p_{jn}^{ind} - p_{jn}^{nc}\right)}_{\mu_{jn}^{multi}} + \underbrace{\left(p_{jn}^{nc} - p_{jn}^*\right)}_{\mu_{jn}^{contract}}. \tag{8}$$

The first component, $\mu_{jn}^{spatial} = p_{jn}^{be} - p_{jn}^{ind}$, is the portion of the markdown due to the spatial configuration of the plants, relative to the source of cattle supply. This portion arises because transportation costs, combined with the Bertrand competition among price-discriminating firms, allow plants to exert market power over the nearest cattle producers. The second component, $\mu_{jn}^{multi} = p_{jn}^{ind} - p_{jn}^{nc}$,

TABLE 3 Fed cattle prices and markdowns in the baseline equilibrium.

	U.S. fed cattle share (%)	Price ($/cwt)	Markdown decomposition: Full (%)	Full ($/cwt)	Spatial ($/cwt)	Multi-plant ($/cwt)	Contract ($/cwt)	Capacity effect ($/cwt)
Full U.S.	100%	142.66	2.6%	3.69	1.98	0.24	1.48	1.16
Top 5 cattle producing states								
Kansas	22.0%	143.63	2.7%	3.81	1.97	0.30	1.54	0.94
Nebraska	20.4%	143.70	2.3%	3.35	1.93	0.22	1.19	1.11
Texas	19.6%	140.52	3.7%	5.24	2.14	0.23	2.87	1.26
Colorado	7.7%	143.06	2.7%	3.93	2.21	0.31	1.41	0.72
Iowa	7.4%	142.72	2.3%	3.34	1.76	0.19	1.40	1.49

Note: The baseline equilibrium is computed with the model calibrated to the 2022 data. Results are converted to and presented in units of $/cwt.

is the portion of the markdown due to firms' ownership of multiple plants. This portion arises when firms internalize the business-stealing effect of competition for cattle supplies among multiple plants that they own. The final component, $\mu_{jn}^{contract} = p_{jn}^{nc} - p_{jn}^{*}$, is the portion that arises due to the use of AMAs in the industry. This portion arises because firms have additional incentives to lower their cash bids because the price of all contracted supplies is tied to the average spot market price.

An additional value of interest, conceptually separate from the markdown and its decomposition, is the impact of capacity constraints on prices in the model. We define this value as $\nu_{jn} = \left(b - c_0 - t_{jn}\right) - p_{jn}^{be}$, the difference between the plant's breakeven price if capacity constraints were not binding, and its actual breakeven price as described above.

5.2 | Baseline results

We first examine the results on equilibrium prices and markdowns. Table 3 presents the average equilibrium price and the decomposition of markdowns for the full United States and for the top five cattle producing states. We find that the national average of estimated markdowns is $3.69/cwt, or about 2.6% of the national average fed cattle price. About 54% of the markdown, $1.98/cwt, can be attributed to the spatial configuration of plants. The use of AMAs in the market accounts for 40% of the full markdown, while only the remaining 6% of the markdown is due to firms' ownership of multiple plants. Beyond the markdown, binding capacity constraints in the industry lower equilibrium prices by $1.16/cwt. As shown in Table 3, the same patterns largely hold for each of the top five cattle producing states individually. Markdowns are somewhat above the national average in Kansas and Colorado, due to relatively high contracting and multi-plant ownership portions in Kansas and relatively high spatial and multi-plant ownership portions in Colorado. In Texas, where AMA usage is significantly higher than average (see Supporting Information Appendix, Part II), the high contracting markdown leads to a full markdown about 40% above the national average. Nebraska and Iowa, meanwhile, have relatively low markdowns, driven largely by the lower contracting portion in Nebraska and the lower spatial portion in Iowa.

The average estimated markdown of $3.69/cwt may appear modest as a percentage of the equilibrium cattle price, but it is arguably economically significant for cattle producers. Feedlot enterprises are known to operate on thin profit margins,[18] and a price markdown of the estimated

[18]Feedlot profit margins are typically estimated as the difference between the selling price of fed cattle and a "breakeven price" computed for a stylized feeding operation. For example, the USDA monthly estimated returns for fed cattle reported by the USDA, using the High Plains Cattle Feeding Simulator, actually shows an average net loss for the year 2022 (−$3.52/cwt). https://www.ers.usda.gov/data-products/livestock-and-meat-domestic-data.

TABLE 4 Firm-level markdowns and costs in the baseline equilibrium.

Firm	Markdown	Capacity utilization	Procurement distance	Marginal cost ratio	
				Average	Max
JBS	3.81	84%	168	1.01	1.07
Tyson	4.58	96%	138	1.01	1.05
Cargill	3.83	95%	136	1.04	1.08
National Beef	3.78	104%	150	1.09	1.20
Other	2.41	105%	172	1.32	1.71
Industry	3.69	96%	152	1.17	1.71

Note: This table summarizes markdowns and cost in the baseline equilibrium, for each of the top four firms, all other firms, and the entire industry. Markdown, Capacity Utilization, and Procurement Distance are weighted averages across all plants owned by the firm or in the group. Marginal Cost Ratio is the ratio of equilibrium marginal cost to the base marginal cost c_0, with the simple average and maximum values across plants in the group reported.

magnitude (which translates to about $52/head, using the average weight of cattle sold in 2022) could in fact make a sizeable difference in operating profits. Using the total volume of cattle marketed in 2022 as reported by the USDA, the aggregate value of the price markdown for the industry implied by our estimates would be $1.28 billion.

Some heterogeneity across firms and plants in the baseline equilibrium is illustrated in Table 4. As expected, the top four firms have higher markdowns than the smaller "fringe" firms. Among the large firms, JBS has a higher procurement distance in equilibrium because many of its plants are located farther away from the main belt of fed cattle supplies (Figure 2). This location disadvantage appears to limit JBS's ability to exercise market power somewhat, as it has lower markdowns than Tyson or Cargill despite its low capacity utilization and marginal costs.

The industry as a whole is operating at an average 96% capacity utilization in the baseline equilibrium, with National Beef and fringe firms operating at higher capacity than the other large firms. The marginal cost experienced by each plant depends on the quantities they process at the equilibrium price vectors. The Marginal Cost Ratio reported in Table 4 is the equilibrium marginal cost divided by the base marginal cost c_0 (recall Figure 3). Note that National Beef and the fringe have nearly the same (average) capacity utilization but very different (average) marginal costs because National Beef's production is relatively evenly distributed among its three plants, while the fringe has a higher dispersion (some plants are considerably above capacity and consequently have much higher marginal costs).

Figure 4 shows the spatial distribution of county-level average prices and markdowns in the model. Recalling plant locations from Figure 2, we can see that spatial markdowns are typically high in the counties surrounding large and relatively isolated plants, as well as in the eastern and western regions where both fed cattle and processing capacity are scarce. The multi-plant component of the markdown is highest in the Rocky Mountain and Great Lakes regions. In both these regions, JBS operates multiple plants with combined capacities that are much larger than any other plants in the region. Meanwhile, the multi-plant markdown is notably low in areas of Nebraska, Kansas, Colorado, and Texas where multiple large plants owned by different members of the top four firms compete. The contracting portion of the markdown is highest in Texas, Oklahoma, and New Mexico, where AMAs account for 86% of fed cattle transactions. Finally, Figure 4 also shows that equilibrium prices are generally most affected by capacity constraints throughout the Midwest and Great Plains areas that are home to both most of the fed cattle supply and most of the beef packing capacity. Indeed, counties surrounding large plants are often subject to the highest capacity effects. This shows that, despite the high total processing capacity in this region, plants in the model are generally operating at levels where their capacity constraints begin to bind, leading to increased marginal costs for the plants.

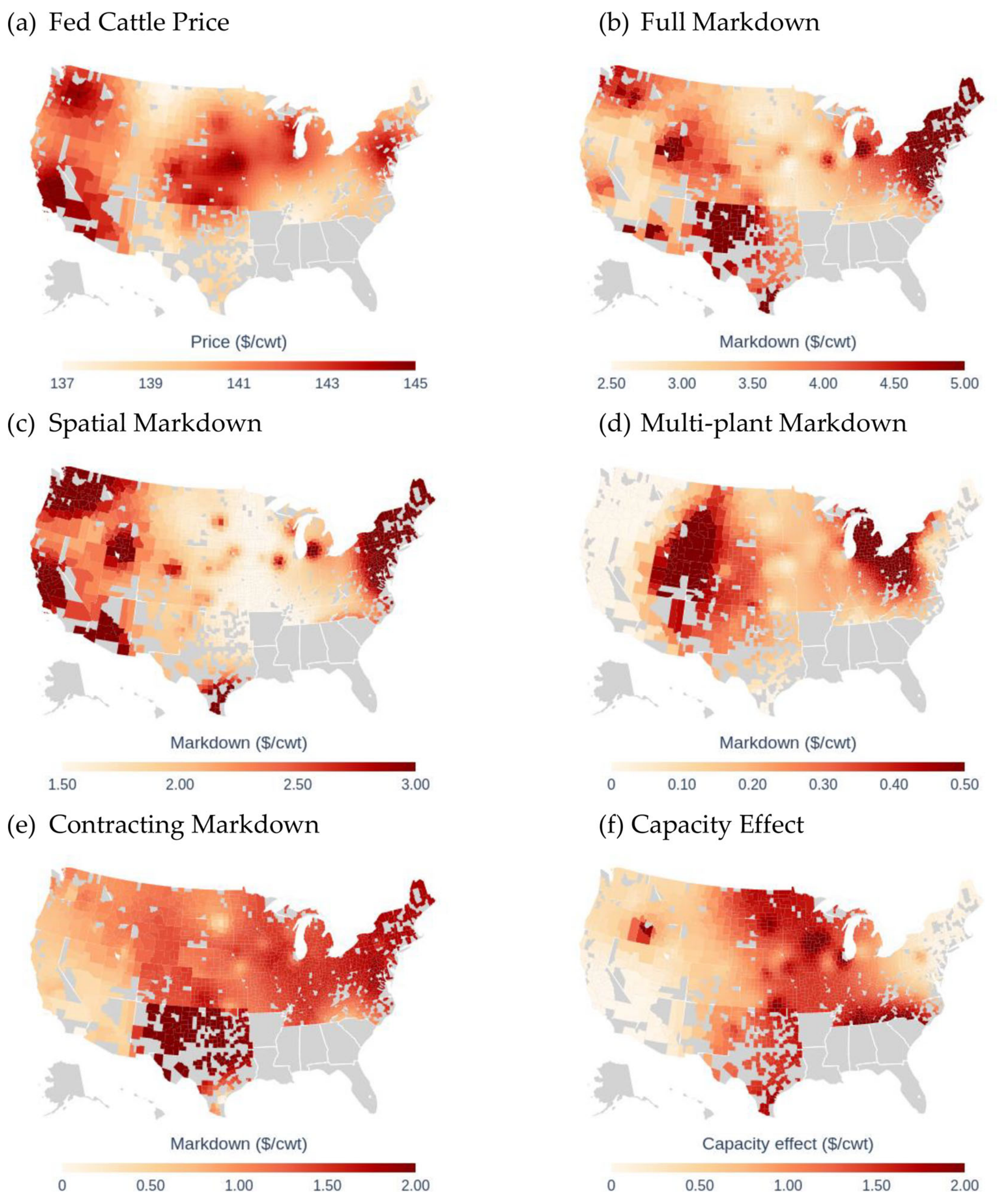

FIGURE 4 County-level price and markdowns. This figure shows the spatial variation in markdowns in the baseline model. Panel (a) shows the equilibrium fed cattle price in each county. Panel (b) shows the average full markdown by county. Panels (c)–(e) show the components of the markdown due to the spatial configuration of plants, firms' ownership of multiple plants, and contracting, respectively. Panel (f) shows the effect of binding capacity constraints on equilibrium prices. Note that each panel has a different scale in order to highlight the regional variation.

5.3 | Robustness to collusion

As noted, the model we study is best interpreted as a short-run price determination model. Although the underlying commodity is physically homogeneous, the spatial nature of the market results in a product-differentiation framework, à la Hotelling, wherein the standard Bertrand–Nash equilibrium notion is appropriate. Yet, key features of the model—the fixed aggregate supply of cattle, and the existence of (soft) capacity constraints—suggest some caution. Specifically, by lowering the incentives to deviate, these features could make collusion a sustainable outcome under the assumptions of the model.

The question posed here is whether, from a putative collusive equilibrium price, individual firms would have an incentive for unilateral deviation. We investigate this possibility by computing the industry equilibrium under the assumption that the top four firms, which account for about 83% of industry processing capacity, operate as a single profit-maximizing entity. With respect to the specification of the model, this collusive scenario can be construed by changing the ownership matrix $\boldsymbol{H}$ (see Appendix B), such that $H_{jk} = 1$ for all plants j and k belonging to these four firms. Having evaluated the firms' profits at this collusive equilibrium, we investigate whether any one of these firms could improve their profit by a small unilateral deviation from the collusive price vector. The results are reported in the Supporting Information Appendix, Part III. We observe that, indeed, each of the four firms would find it profitable to deviate from such a counterfactual equilibrium: by offering a higher cattle price, each firm can gain a larger market share and increase its profits. We conclude that the presumed Bertrand–Nash equilibrium framework is internally consistent, given the fundamentals of the model.

5.4 | Sensitivity to calibrated parameters

The values of some key parameters of the model were chosen based on limited information. In particular, the logit price-sensitivity parameter α and the marginal cost parameter c_0 are jointly calibrated to ensure that the average equilibrium cattle price, and the average distance between cattle sellers and packing plants, match available data. Similarly, the transportation cost parameter was based on estimated cattle hauling rates. To investigate how the model's results may be affected by the values of these parameters, we solve the baseline model when each of them, in turn, is increased or decreased by 20%. The results are reported in the Supporting Information Appendix, Part IV. We find that the baseline results are rather robust to the values of these parameters. Changes in the transportation cost parameter of the magnitude we considered have essentially no discernible effects of equilibrium outcomes. Change in the marginal processing cost parameter do affect the equilibrium price of fed cattle (with essentially full pass-through), but hardly affect the estimated markdown. Changes in the price sensitivity parameter α, on the other hand, have more noticeable effects (in the expected direction). A higher value of this parameter leads to slightly higher cattle prices and a lower markdown, and the opposite is observed with a lower parameter value. The decomposition of the estimated markdown, on the other hand, is extremely robust across all parameter sensitivity scenarios.

5.5 | Mill price formulation

In the foregoing, we have argued that the price-discrimination formulation of the oligopsony market that we use is rooted in how the cash market in this industry operates—packing firms' procurement agents do negotiate purchases and prices directly with feedlot managers. The alternative would be to presume the so-called "mill price" formulation, whereby firms compete by setting plant-level prices for delivered cattle (with transportation costs implicitly paid by farmers). The presumption of price

TABLE 5 Fed cattle prices and markdowns in the mill price equilibrium.

	U.S. fed cattle share (%)	Price[a] ($/cwt)	Markdown decomposition Full (%)	Full ($/cwt)	Spatial ($/cwt)	Multi-plant ($/cwt)	Contract ($/cwt)	Capacity effect ($/cwt)
Full U.S.	100%	143.06	2.8%	3.97	2.21	0.24	1.51	1.35
Top 5 cattle producing states								
Kansas	22.0%	144.21	2.6%	3.78	2.10	0.29	1.38	1.18
Nebraska	20.4%	143.66	2.7%	3.89	2.14	0.23	1.52	1.32
Texas	19.6%	143.21	3.0%	4.25	2.68	0.20	1.37	1.20
Colorado	7.7%	143.90	2.8%	4.03	2.38	0.32	1.32	0.83
Iowa	7.4%	142.98	2.7%	3.83	1.92	0.20	1.72	1.74

Note: This table shows key market outcomes in the mill-price formulation model. In this formulation, parameters are calibrated exactly as in the baseline equilibrium, but firms are assumed to compete by setting a plant-gate mill price, with feedlots paying the transportation cost to ship supply to the plant. Results are converted to and presented in units of $/cwt.

[a]Reported price is the average price, net of transportation costs, for feedlots in the model.

discrimination we have followed above, of course, is supported by theory. Specifically, it is consistent with the (oligopoly) results of Thisse and Vives (1988) who show that, when firms choose a spatial price policy and then compete in prices in an oligopoly setting, price discrimination by all firms is the unique Nash equilibrium.

In this section, we provide results for our oligopsony equilibrium model under the alternative assumption that packing firms compete by setting plant-gate prices, rather than competing directly in local prices. In this formulation, feedlots' supply decisions are based on each plant's mill price and the (exogenously given) transportation cost between the plant and feedlot. This alternative formulation is instructive on a few accounts. First, despite the fact that theory favors the price-discrimination formulation, the mill price setup is an often-used assumption in much applied work (Graubner et al., 2021). Second, the simple observation that the cash market operates with seemingly decentralized bids in local markets is not sufficient, per se, to rule out the mill price policy—it is possible for the constellation of prices offered by firms' procurement agents to be constrained to satisfy the mill price formulation. The results of Thisse and Vives (1988) favor the price-discrimination model in an unfettered policy-then-price competition framework, meaning that a mill price policy across the industry would require a degree of collusion between firms. Hence, the comparison of equilibria under the alternative price policies may highlight the potential for collusion through this channel.

Results for the mill price formulation are reported in Table 5.[19] These results align with expectations—the mill price formulation yields less competitive outcomes than the price discrimination setup. The full markdown is about 8% higher with mill pricing than with price discrimination. Despite these increased markdowns, however, the average fed cattle price to feedlots (net of transportation costs) is about the same as in the baseline. This is due to lower average transportation costs under mill pricing, with cattle traveling an average of 129 miles from feedlot to plant, compared to 152 miles in the baseline. Concerning spatial heterogeneity, relative to the baseline, the mill price markdown is around 15% higher in Nebraska and Iowa, relatively unchanged in Kansas and Colorado, and 20% lower in Texas. For all five states, the spatial markdown is higher under mill pricing than in the baseline, and the multi-plant portion of the markdown is relatively unchanged. Nebraska

[19]Note that computation of equilibria with the mill price formulation requires appropriate changes in the equilibrium conditions derived earlier, which we omit here for space reasons.

and Iowa have notably higher contracting markdowns under mill pricing, while in Texas this portion is significantly lower.

6 | COUNTERFACTUAL POLICY SCENARIOS

Having characterized the baseline equilibrium, we now consider a set of policy-relevant scenarios. In particular, we examine in detail six counterfactual experiments. The first two experiments model the equilibrium impacts of large supply shocks, mimicking the peak and trough of the cattle cycle (Rosen et al., 1994). This is motivated by widely-held beliefs that the cattle cycle may yet have profound effects on market outcomes. For example, Crespi et al. (2010) show conceptually and empirically that the interaction between the cattle cycle and market power can lead to lower fed cattle prices.

The next two scenarios focus on elements that have been salient in recent cattle market commentaries. One has to do with so-called multi-plant coordination (Pudenz & Schulz, 2024). This is a property that is typically taken for granted in I.O. models (through the ownership matrix used in standard Bertrand–Nash equilibrium, see Appendix B), and which we have maintained in the baseline. In the counterfactual this coordination is relaxed such that, effectively, the scenario is one where each firm only owns one plant.

The next scenario focuses on the controversial role of AMAs (Anderson et al., 2022; Garrido et al., 2022). As noted above, our baseline model includes pre-committed supplies at the level observed in 2022. The counterfactual reduces the level of such supplies to a maximum of 50%, as suggested by some current policy proposals.

The final two scenarios highlight the effects of plant entry and exit on model outcomes. These experiments are motivated by ongoing policy efforts to strengthen the competitiveness and resilience of the meat supply chain through a subsidized expansion of independent processing capacity (USDA-AMS, 2022; MacDonald, 2024), as well as recent high-profile temporary plant closures due to a fire and the COVID-19 pandemic.

6.1 | Counterfactual experiments

The details of the six policy experiments are as follows:

a. ***Supply increase scenario***: We model an exogenous 15% increase in the supply of fed cattle. We assume that the increase is evenly spread, with each county's supply increasing by 15%. We maintain the assumption that fed cattle are processed into beef in fixed proportions, and therefore assume that this supply shock will increase the supply of beef by 15%. For this supply increase scenario (as well as the supply decrease scenario), maintaining a fixed beef price b is no longer appropriate. Conceivably, the retail price (and the wholesale price) will adjust as the cattle/beef supply shifts. We assume an elasticity of beef demand of -0.5 based on Tonsor et al. (2018), meaning that the postulated shift in beef supply will lead to a 30% decrease in the price of beef.
b. ***Supply decrease scenario***: We model an exogenous 15% decrease in the supply of fed cattle, using the same assumptions as in the supply increase scenario. We thus assume that this supply shock leads to a 15% decrease in the supply of beef and a 30% increase in beef price as the equilibrium moves along the demand curve.
c. ***Independent plants scenario***: For this scenario we compute the equilibrium assuming all plants maximize their profits independently. Note that in this counterfactual we allow plants' marginal costs to adjust as their quantities change, making this exercise distinct from the computation of p_{jn}^{ind} in the markdown decomposition.

d. ***Limited contracting scenario***: In this scenario, we limit the supply obtained via contracting in each county to no more than 50% of the volume transacted in each region. This ceiling aligns with proposals in the U.S. Congress to limit AMA transactions by establishing a mandatory minimum share of negotiated transactions.
e. ***Plant entry scenario***: We model the entry of a new independent plant with 2000 head-per-day capacity in Glenwood, Iowa. This scenario was chosen due to the planned construction of such a plant (Cattlemen's Heritage Beef, 2023). Note that because our model is calibrated to 2022 conditions, we are not forecasting the impact of this new plant, but rather analyzing how the hypothetical existence of the plant impacts key model outcomes.
f. ***Plant exit scenario***: We model the exit from the market of Tyson's 6000 head-per-day plant in Holcomb, Kansas. This scenario is motivated by the shutdown of this plant for several months, due to a fire, in late 2019 (Polansek, 2019). However, we again note that we are not analyzing the actual event. Instead, we examine how the exit of this plant impacts equilibrium outcomes in the model.

6.2 | Counterfactual results

Table 6 summarizes the results concerning the foregoing counterfactual scenarios, in terms of market outcomes compared to the baseline. We find that the average fed cattle price moves in the expected direction in each scenario, with interesting patterns in both the magnitude of the price changes and the mechanisms driving them.

In the supply increase and supply decrease scenarios, markdowns change little relative to the baseline, while capacity constraints play a larger role in price changes. The asymmetry of the price changes is noteworthy. Compared to the baseline, the exogenous 15% increase in supply leads to a $53/cwt decrease in the average fed cattle price. This is primarily due to the assumed 30% decrease in the downstream beef price, but notably $3.04/cwt of the change is due to capacity constraints binding more tightly. Meanwhile, the exogenous 15% decrease in supply leads to a $50/cwt increase in the fed cattle price, driven by the assumed increase in the beef price and a $0.54/cwt decrease in the impact of capacity constraints compared to the baseline. Thus, prices decrease by more in the

TABLE 6 Average market outcomes by scenario.

		Markdown decomposition					
	Price ($/cwt)	Full (%)	Full ($/cwt)	Spatial ($/cwt)	Multi-plant ($/cwt)	Contract ($/cwt)	Capacity effect ($/cwt)
Baseline	142.66	2.6%	3.69	1.98	0.24	1.48	1.16
Supply increase	89.60	4.2%	3.78	2.20	0.27	1.31	4.20
Supply decrease	193.15	1.9%	3.62	2.09	0.20	1.33	0.62
Independent plants	144.23	2.0%	2.83	2.31	0.00	0.52	0.78
Limited contracting	143.98	2.2%	3.14	2.33	0.21	0.60	0.90
Plant entry	142.95	2.5%	3.59	1.95	0.21	1.42	1.01
Plant exit	141.65	2.6%	3.72	2.17	0.24	1.32	2.06

Note: This table shows key market outcomes in the baseline model and the four counterfactual scenarios. For the baseline equilibrium and each counterfactual scenario, the national average price, markdown, decomposition of the markdown, and effect of capacity constraints are reported. Results are converted and presented in units of $/cwt.

supply increase scenario than they increase in the supply decrease scenario, due to the asymmetric impact of capacity constraints on prices. When capacity constraints bind tighter, plants' marginal costs rise steeply, and prices are driven lower. On the other hand, when capacity constraints ease, marginal costs eventually hit their base level (c_0 in the model) and do not fall further, limiting the upward pressure on prices.

In the independent plants and limited contracting scenarios, we see changes in the markdown playing a larger role than capacity effects. Compared to the baseline, the full markdown decreases by 23% in the independent-plant scenario, due to decreases in both the multi-plant and contract components of the markdown. In the limited contracting scenario, the markdown is 15% lower than the baseline, driven by the contracting portion of the markdown. However, because the markdown is small relative to the fed cattle price in the baseline, the average fed cattle price increases by only about 1% in each of these scenarios.

In the plant entry and exit scenarios, markdowns change little compared to the baseline, with capacity effects contributing more to the resulting price changes. The plant entry in Glenwood, Iowa eases capacity constraints slightly, leading to a \$0.29/cwt increase in the average fed cattle price. On the other hand, the exit of the Tyson plant in Holcomb, Kansas nearly doubles the capacity effect on prices, leading to a \$1.01/cwt drop in the average fed cattle price. Note once again the asymmetry of these results—the exit of the 6000 head per day Holcomb plant has about 3.5 times the price impact as the entry of the 2000 head per day Glenwood plant.

7 | DISCUSSION AND CONCLUSIONS

The issue of market power in the beef packing industry has come under scrutiny in recent years due to an increased spread between beef prices and fed cattle prices. This spread began to rise in 2015, with large spikes due to the 2019 Tyson plant fire in Holcomb, Kansas, and disruptions in the spring of 2020 from COVID-19. Analysis of the price spread has focused, inter alia, on the exercise of market power by the packing plants, with some special attention on the use of AMAs in the industry and firms' ownership of multiple plants.

In this paper, we show that in a calibrated Bertrand–Nash model of cattle procurement competition, price "markdowns"—the hallmark of buyer power—are moderate. In the baseline, the estimated markdown is \$3.69/cwt, or about 2.6% of cattle prices. Most of the markdown (about 55%) is attributable to the inherent spatial configuration of the industry, where cattle supplies are distributed over a wide portion of rural areas, whereas beef packing plants are large and operate in specific locations. The existence of the large portion of supplies that are pre-committed via AMAs is the next-most important determinant of the price markdown, while multi-plant ownership, per se, appears to have a minor influence. We also note that the extent of model-estimated markdowns, while modest as a fraction of cattle prices, may nonetheless have economically significant impacts on the profitability of feedlots and upstream operators in the cattle industry.

Some caveats are in order at this juncture. Our model focuses on packers' competition on the demand side, taking cattle supplies as given. This price determination approach is defensible based on key structural features of the industry. Although feedlots may have some limited week-to-week flexibility in cattle marketing choices, cattle availability for slaughter is clearly constrained by the long production lags that characterize the cattle-beef supply chain. Hence, the (short-run) impacts of buyer power on cattle prices can be meaningfully studied in our model, albeit its structure limits the research questions that can be posed. In particular, we cannot assess the extent to which the exercise of market power may affect long-run cattle supply decisions. Despite these limitations, the results of this paper reveal some key insights about markdowns and prices in the industry. First, we find that AMA usage does increase markdowns as predicted by economic theory—in the baseline equilibrium, contracting increases the markdown by two-thirds over what it would be with only the spatial and multi-plant components. However, because the spatial and multi-plant components of the markdown are small relative to the fed cattle price, this large percentage increase in the markdown causes relatively minor changes in the market price.

Second, the results highlight the importance of the spatial nature of competition in the industry. Spatial differentiation gives plants some degree of market power, but the clustering of plants owned by different firms around the geographically concentrated fed cattle supplies limits the scope for strategic coordination by the multi-plant firms. Indeed, in the data used to calibrate the model, the capacity-based Herfindahl–Hirschman Index (HHI) of the industry is 1872 (qualifying the industry as moderately concentrated according to the Department of Justice) and the four-firm concentration ratio is 83%. In the counterfactual scenario with all plants operating independently, the HHI would decrease to 399 (putting the industry well into competitive territory), and the four-firm concentration ratio would fall to 23%. Whereas such a reduction in concentration would reduce the markdown somewhat, it would result in a very marginal increase in the fed cattle price.

Finally, our model suggests that capacity constraints may play a larger role in the increased spread between beef and cattle prices than either AMAs or multi-plant ownership. Recent data trends are consistent with this idea. The rising price spread beginning in 2015 coincided with a shift from a decreasing to increasing trend in cattle slaughter. Slaughter volumes began decreasing again in 2022, accompanying a decreasing trend in the price spread, though the level of the spread remains above historical levels. While the importance of capacity constraints in the beef packing industry has been acknowledged previously, this study furthers the analysis by incorporating (soft) capacity constraints into a structural, spatially-explicit model of the industry. In the model, capacity constraints play an especially important role when the constraints become more binding, as in the counterfactual scenario of an increase in fed cattle supply.

As noted previously, key features of the beef packing industry, including highly concentrated firms, spatial differentiation, and capacity constraints, make a perfectly competitive benchmark ill-defined. In this paper, therefore, we characterize outcomes in a baseline model of imperfect competition that is consistent with the industry's structure. Beef packing firms acquire cattle in the negotiated cash market by price bids, and we model price determination as a Bertrand–Nash price competition in an oligopsony framework for differentiated products. Whether this benchmark model aligns with actual conduct in the industry may deserve further scrutiny. The particular price-discrimination formulation we have privileged is certainly defensible, based on apparent industry business practices. What we have not generally addressed, in this paper, is the possibility of collusive behavior among packers (beyond the robustness exercise reported in Section 5).

More general questions about collusion may be of interest. Repeated interactions, for example, are known to facilitate tacit collusion (e.g., Ivaldi et al., 2003). In fact, in such a setting, AMA-like contracts may exacerbate market power (Hatfield & Lowery, 2023). The required dynamic features to characterize collusion in such a fashion, however, are not easily adapted to the structural details embedded in our model. Alternatively, a reduced-form way to assess the potential for collusion in our modeling framework could rely on a conduct parameter along the lines of Miller and Weinberg (2017), whereby firms behave as if they partially internalize the impacts of their pricing on other firms' profits. Modeling collusion in a meaningful way, for the cattle and beef industry setting of interest, may require some care. For the current short-run price determination framework, with perfectly inelastic supply, perfect collusion would drive cattle prices to zero, hardly an instructive conclusion. Partial collusion among a subset of firms, perhaps more plausible, may still call for a careful assessment of the role of capacity constraints, perhaps beyond the convenient parameterization used in this paper.

Study of the welfare implication of market power in this industry will also benefit from an expanded framework. The efficiency implications of cattle price markdowns, beyond the redistribution of surplus between packers and farmers, ultimately depend on the supply-depressing effects caused by the exercise of market power. This is a question the current model, which takes cattle supplies as given, cannot address. A coherent model of production decisions along the cattle supply chain requires handling dynamic features that, in the context of an imperfectly competitive structure, would present non-trivial methodological challenges. A related but distinct question relates to the impacts of market power on consumer welfare, and how this is mediated by the relation between packers and the retail sector. These are important matters that warrant continued investigation.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A: OPTIMALITY CONDITIONS WITH INCREASING MARGINAL COST

When the firm's objective function is given by equation (4) in the text, the optimality conditions defining the firm's best response functions are:

$$\frac{\partial \Pi_f(\mathbf{p})}{\partial p_{jn}} = M_n \left[-s_{jn}(\mathbf{p}_n) + \sum_{k \in \mathcal{J}_f} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}} (b - t_{kn} - p_{kn}) \right] - \sum_{k \in \mathcal{J}_f} \frac{\partial C(q_k(\mathbf{p}))}{\partial q_k} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}} M_n - \frac{\partial \overline{p}_r(\mathbf{p})}{\partial p_{jn}} \sum_{\ell \in r} \sum_{k \in \mathcal{J}_f} \overline{x}_{k\ell} = 0. \tag{A1}$$

Recall that the assumed cost function satisfies:

$$C(q_j) = c_0 q_j + \int_{K_j}^{q_j} \gamma \left(\frac{q}{K_j} - 1 \right)^{\lambda} dq.$$

For the domain where $\mathbf{1}\{q_j > K_j\} = 0$, the marginal cost is simply:

$$\frac{\partial C(q_j(\mathbf{p}))}{\partial q_j} = c_0,$$

whereas for the domain where $\mathbf{1}\left\{q_j > K_j\right\} = 1$ the marginal cost is:

$$\frac{\partial C\left(q_j(\mathbf{p})\right)}{\partial q_j} = c_0 + \gamma\left(\frac{q_j}{K_j} - 1\right)^{\lambda}$$

Hence, if $c\left(q_k\right)$ denotes the marginal cost function as given in Equation (5) in the text, then the condition in (A1) can be stated as:

$$M_n\left[-s_{jn}(\mathbf{p}_n) + \sum_{k \in \mathcal{J}_f} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}\left(b - c\left(q_k(\mathbf{p})\right) - t_{kn} - p_{kn}\right)\right] - \frac{\partial \overline{p}_r(\mathbf{p})}{\partial p_{jn}} \sum_{\ell \in r} \sum_{k \in \mathcal{J}_f} \overline{x}_{k\ell} = 0. \tag{A2}$$

APPENDIX B: COMPUTATION OF EQUILIBRIA

In this appendix, we provide some details on our adaptation of the Morrow and Skerlos' (2011) algorithm to an oligopsony model with differentiated products. For notational clarity we focus on the case where there is no contracting and capacity constraints are not binding (marginal processing costs are constant). For such a case, for the price-discrimination formulation used in the main text, the optimality conditions are:

$$-s_{jn}(\mathbf{p}_n) + \sum_{k \in J_f} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}\left(b - p_{kn} - m_{kn}\right) = 0, \quad \forall j \in J_f, \quad \forall f, \text{ and } n = 1, 2, \ldots, N, \tag{B1}$$

where $m_{k\ell} \equiv c_0 + t_{k\ell}$ denote "total" marginal costs, that is, inclusive of processing and transportation costs. Note that there are $J \times N$ such equations, which define the firms' best response functions and are solved for N equilibrium price vectors, each one of which is $J \times 1$.

Let $\mathbf{S}(\mathbf{p}_n)$ be the $J \times J$ matrix of substitution terms, that is, with elements $S_{ji} \equiv \partial s_{jn}(\mathbf{p}_n)/\partial p_{in}$, and let $\mathbf{H}$ denote the $J \times J$ ownership matrix, which has elements $H_{ji} = 1$ if plants i and j belong to the same firm, and $H_{ji} = 0$ otherwise. Combining the information of these two matrices yields the $J \times J$ matrix $\mathbf{\Omega}(\mathbf{p}_n) \equiv \mathbf{S}(\mathbf{p}_n) \circ \mathbf{H}$, where $\circ$ denotes the Hadamard product (i.e., element-by-element) of two matrices of the same dimension. The Bertrand–Nash equilibrium conditions in (B1) can then be expressed in matrix form as:

$$\mathbf{s}(\mathbf{p}_n) - \mathbf{\Omega}(\mathbf{p}_n)[b\boldsymbol{\iota} - \mathbf{m}_n - \mathbf{p}_n] = 0, \tag{B2}$$

where $\mathbf{s}(\mathbf{p}_n)$ is the vector of market shares in county n, $\boldsymbol{\iota}$ is a $J \times 1$ vector of ones, and $\mathbf{m}_n$ is the vector of county-specific total marginal costs. This is the oligopsony-equivalent of the standard Bertrand–Nash oligopoly solution for differentiated products (e.g., Nevo, 2001). [But note the sign change convention in the definition of the matrix $\mathbf{\Omega}(\mathbf{p}_n)$].

The fixed-point iteration to compute Nash equilibria commonly used in oligopoly models (e.g., Nevo 2011), which is labeled η-FPI by Morrow and Skerlos (2011) and Conlon and Gortmaker (2020), can readily be adapted to our oligopsony context. Specifically, from (B2) the Nash equilibrium can be expressed as:

$$\mathbf{p}_n^* = (b\boldsymbol{\iota} - \mathbf{m}_n) - \boldsymbol{\Omega}^{-1}(\mathbf{p}_n^*)\mathbf{s}(\mathbf{p}_n^*). \tag{B3}$$

This equation explicitly shows that the equilibrium price entails a "mark-down" from the vector of plant's marginal value products $(b\boldsymbol{\iota} - \mathbf{m}_n)$. The η-FPI is derived directly from (B3).

Alternatively, to adapt the more efficient Morrow and Skerlos (2011) fixed point algorithm to our oligopsony case, we start with the decomposition $\mathbf{S}(\mathbf{p}_n) = \boldsymbol{\Lambda}(\mathbf{p}_n) - \boldsymbol{\Gamma}(\mathbf{p}_n)$, where $\boldsymbol{\Lambda}(\mathbf{p}_n)$ is a diagonal matrix, such that $\boldsymbol{\Omega}(\mathbf{p}_n) = [\boldsymbol{\Lambda}(\mathbf{p}_n) - \mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)]$. Substituting into (B2) yields.

$$\mathbf{s}(\mathbf{p}_n) + \boldsymbol{\Lambda}(\mathbf{p}_n)\mathbf{p}_n - \boldsymbol{\Lambda}(\mathbf{p}_n)(b\boldsymbol{\iota} - \mathbf{m}_n) + [\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)][(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] = 0 \tag{B4}$$

from which we get

$$\mathbf{p}_n = (b\boldsymbol{\iota} - \mathbf{m}_n) - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)][(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n). \tag{B5}$$

This is the basis for the Morrow and Skerlos (2011) ζ-FPI procedure in our setting:

$$(b\boldsymbol{\iota} - \mathbf{m}_n) - \zeta(\mathbf{p}_n) \mapsto \mathbf{p}_n, \quad \zeta(\mathbf{p}_n) \equiv \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)][(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] + \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n). \tag{B6}$$

Note the root source of the computational advantage of the ζ-FPI approach: At each step, the algorithm simply requires inversion of the diagonal matrix $\boldsymbol{\Lambda}(\mathbf{p}_n)$ (as opposed to inversion of the dense matrix $\boldsymbol{\Omega}(\mathbf{p})$ as in the standard algorithm).

With the given definition of the $\zeta(\mathbf{p}_n)$ function, we have:

$$\begin{aligned} &(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n - \zeta(\mathbf{p}_n) = \\ &(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)][(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n) \end{aligned} \tag{B7}$$

such that:

$$\begin{aligned} \boldsymbol{\Lambda}(\mathbf{p}_n)[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n - \zeta(\mathbf{p}_n)] &= [\boldsymbol{\Lambda}(\mathbf{p}_n) - \mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n)][(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] - \mathbf{s}(\mathbf{p}_n) \\ &= \boldsymbol{\Omega}(\mathbf{p}_n)[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n] - \mathbf{s}(\mathbf{p}_n), \end{aligned} \tag{B8}$$

where the right-hand-side is the vector of first-order conditions in (B2). Hence, the ζ-FPI, for our oligopsony case, terminates when.

$$\left\| \boldsymbol{\Lambda}(\mathbf{p}_n^i)\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n^i - \zeta(\mathbf{p}_n^i)\right] \right\| < tol, \tag{B9}$$

where *tol* is a preset tolerance level (e.g., $tol = 10^{-8}$). Conlon and Gortmaker (2020, footnote 65) note a similar termination rule for the standard demand case.