Spatial Competition and Buyer Power in the U.S. Beef Packing Industry *

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PRELIMINARY

Comments are welcome

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Abstract: We develop a spatially-explicit model of the U.S. beef packing industry to analyze key questions related to competition and efficiency in an oligopsony setting. Cattle supplies are modeled at the county level, and packing plants' location, capacity, and ownership are taken as given, with volumes representing 2022 observed data. Packing firms procure negotiated cattle for their plants by competing in prices in each local (county) market, while accounting for transportation costs and pre-existing contracted supplies obtained via alternative marketing arrangements. The calibrated model is then solved for the Bertrand-Nash equilibrium prices. We compute the average markdown in the price packers pay for fed cattle and decompose it into three components: the portion due to the inherent spatial oligopsony power in the industry; the amount due to an aspect of market concentration (firms owning multiple plants); and, the component due to contracting in the industry. We find that, in the computed equilibrium, markdowns are modest, about $3.32/cwt or 2.3% of the fed cattle price, on average. About 56% of this markdown is due to the spatial configuration of plants, 39% is due to pre-contracted supplies, and only 5% of the markdown is attributed to multi-plant ownership by firms. Separately from markdowns, we also characterize the impact of capacity constraints and find they lower fed cattle prices by 0.7% on average. In addition to analyzing the baseline equilibrium, the model is used to simulate counterfactual scenarios to highlight specific policy-relevant questions. We find that markdowns are reasonably robust across counterfactuals, decreasing moderately when plants operate independently and when the use of contracting is limited. In these scenarios, cattle prices per se are most affected by capacity constraints, as due to a major plant closure or an upward swing in the cattle cycle.

Keywords: Bertrand-Nash equilibrium, buyer power, oligopsony, price markdown, price discrimination, procurement contracts, spatial competition, …

JEL Codes: 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 and 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 and MacDonald 2022). The main concern here is that buyer power can result in noncompetitive "markdowns" on cattle prices paid to producers. 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, Outlaw, and Anderson 2021). Concerns over market power in beef packing typically focus on packers' procurement of cattle and the potential exercise of oligopsony power (Garrido et al. 2022; Bolotova 2023). The Biden administration initiative to promote competition in the American economy (White House 2021) 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 US 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, Dong and Fuglie 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%.[1]

A specific issue related to market power in the cattle and beef industry concerns the role of procurement contracts known as "alternative marketing arrangements" (AMAs). A distinctive feature of AMAs is that these contracts are typically settled based on the average spot price in the market at the time of delivery (often, a USDA-AMS reported regional price). The prevalence of these procurement contracts has increased considerably over the last decades, and, at present, AMAs account for about 70% of cattle supplies. The main concern is that, having obtained a large portion of cattle via such contracts, beef packing firms may strategically underbid in the cash market thereby depressing cattle prices. Economic theory implies that such arrangements should in fact influence packers' pricing incentives (Xia and Sexton 2004; Garrido et al. 2022; Moschini and Smith 2024). Contracts such as AMAs also serve as powerful vertical coordination devices, however, with possibly large efficiency gains for all market participants (Koontz and Lawrence 2010; Crespi and Saitone 2018). Furthermore, the extant empirical evidence on the impact of AMAs suggests that their influence on market outcomes may be small (Xia, Crespi, and Dhuyvetter 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 key sources of market power in agriculture. Second, the extent of market power is often assessed (implicitly or explicitly) vis-à-vis perfect competition.[2] A perfectly competitive benchmark may be ill-defined, however, when in fact

[1] See Wohlgenant (2013) for a comprehensive review of earlier work.

[2] For example, Lusk, Tonsor, and Schulz (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.

packing firms are highly concentrated, spatially differentiated, and operate under capacity constraints. Put differently, "competition" under such structural conditions is bound to display some market power. The relevant research objective for this industry, therefore, is not to "detect" the existence of market power, but rather to characterize it vis-à-vis the observed structural configuration of the industry.

In this paper, we provide novel insights into the exercise of oligopsony power in the beef packing industry. A key feature of the industry is the spatial configuration of cattle supplies and packing plants, which, combined with non-trivial costs involved in the transportation of fed cattle, gives rise to spatial differentiation in the transaction of cattle from producers to packers. Given the relevance of this spatial differentiation, we develop a spatially-explicit model of the beef packing industry. We use county-level data on fed cattle supplies from the 2022 U.S. Census of Agriculture, and plant-level information from a variety of sources, to model the spatial configuration of the industry. We assume that plants compete in prices for the available fed cattle supplies in each local (county) market. The cattle supply is taken as given, and thus the price competition we characterize is short-run in nature. The objective is profit maximization, at the packing firm level, while accounting for transportation costs and for the existence of a given amount of supplies pre-committed to each plant via AMAs. We calibrate parameters of the model to 2022 data and compute the resulting Bertrand-Nash equilibrium of the industry.

The model allows us to characterize market power in the computed equilibrium by calculating average national and county-level markdowns on fed cattle prices. We then 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 modest—we find $3.32/cwt or about 2.3% of the fed cattle price, on average. About 56% of the markdown is due to the spatial configuration of

plants, 39% is due to contracting, and only 5% 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 (Peel 2021; Azzam and Dhoubhadel 2022; Bina et al. 2021; MacDonald 2024), 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 capacity constraints lower fed cattle prices by about 0.7% in the baseline model.

The model also permits the simulation of counterfactual scenarios. We model 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 about 20% in both the independent plant and limited contracting scenarios. However, because the markdown is small relative to the fed cattle price in the baseline, these changes lead to small changes (less than 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. Our results, at this stage, are not meant to describe how the beef and cattle industry actually performs. Rather, our immediate objective is to characterize how the industry would be expected to perform in a standard equilibrium context. 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 evaluate 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 Bertrand-Nash formulation that is fairly standard in industrial organization research. Whether more nuanced conduct hypotheses, including the possibility of collusive behavior, better match observed market outcomes is a question left for future research.

2. The Cattle-Beef Industry: A Brief Background

Before proceeding to the data and modelling, 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 can be categorized along two axes: live or dressed weight; and, free on board (FOB) or delivered pricing (USDA-AMS 2020; USDA-GISPA 2014).[3] Live weight refers to the weight of the animal at the feedlot, prior to transportion 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.

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 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 five 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

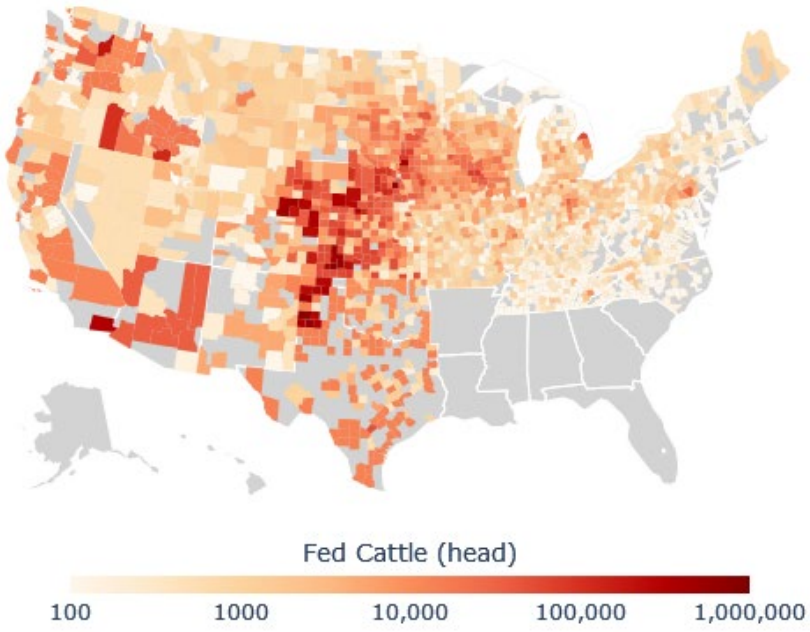
[3] This use of the term "FOB" in USDA's cattle price reporting, essentially referring to prices at the farm, has a somewhat different interpretation than commonly used when describing price policies by buyers in an oligopsony market (e.g., Graubner, Salhofer, and Tribl 2021).

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. The sales volumes from counties accounting for around 23% of the national total are redacted by the USDA for confidentiality reasons. Because excluding such a large portion of supply would distort the analysis, we use the state-level Census of Agriculture values to assign each redacted county a value such that the county totals within each state add up to the correct value. 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 comes from the top five cattle producing states of Kansas, Nebraska, Texas, Colorado, and Iowa. **Figure 1** shows the spatial distribution of fed cattle supplies.

Figure 1. County-level Fed Cattle Supplies in 2022



Note: 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. Data is from the 2022 USDA Census of Agriculture Cattle On Feed – Sales for Slaughter.

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 includes ownership information, allowing us to match specific plants with the firms in CBW data, and their addresses, allowing us to precisely locate plants in space.[4]

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 judgement 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 **Appendix A** 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** shows summary statistics for the packing plants in our data set, and **Figure 2** shows their locations.

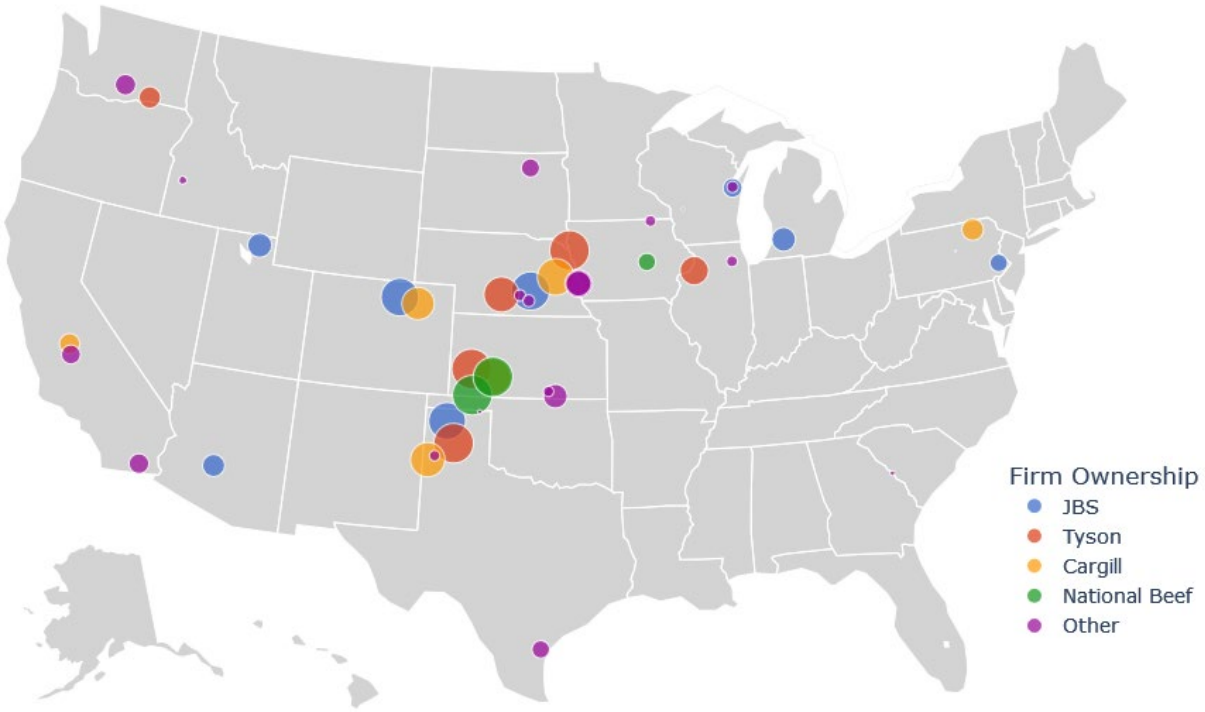
Table 1. Beef Packer Summary Statistics

	Number of Plants	Average Capacity	Total Capacity
JBS	8	3,144	25,150
Tyson	6	4,600	27,600
Cargill	6	3,700	22,200
National Beef	3	4,400	13,200
Other	20	921	18,415
Total	43	2,478	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.

[4] 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



Note: 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. Based on data from *Cattle Buyers Weekly*, USDA FSIS, and various market and news reports.

Comparing **Figure 1** and **Figure 2**, we can see a clustering of fed cattle supplies and beef processing. 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.

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 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 two or three 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.[5] Thus, in units of farm-gate weight, the price received by the producer is $p_{jn}[1 - \sigma_{jn}]$. We assume that the pencil-shrink factor, $\sigma_{jn} = \sigma(d_{jn})$, 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:

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

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. Even without the spatial dimension, characterization of price competition equilibria under capacity constraints is non-trivial and may require mixed strategies (Kreps and Scheinkman 1983). The product differentiation induced by the spatial configuation of cattle supply and demand complicates matters further, and makes such an approach computationally unattractive.

[5] 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.

Whereas the representation in equation (1) is best viewed as a convenient parameterization of a canonical spatial equilbrium 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:

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

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. [6]

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 $\bar{x}_{jn}$ 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 $M_n = Q_n - \sum_j \bar{x}_{jn}$. The amount of cattle procured on the spot market by plant j in market n, therefore, can be written as $s_{jn}(\mathbf{p}_n)M_n$.

[6] An alternative rationalization of the logit representation of equation (2) arises from an auction framework (Crespi and 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 $\mathbf{p}_n$.

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

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

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 $t_{jn} = t(d_{jn})$ 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 $C(q_j(\mathbf{p}))$, where $q_j(\mathbf{p}) = \sum_{n=1}^{N} \left[s_{jn}(\mathbf{p}_n) M_n + \bar{x}_{jn} \right]$ is the total number of cattle processed at plant j.[7] 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:

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

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 (a) transportation is provided by a competitive industry at a

[7] 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.

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:

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

where c_0 is the base marginal cost, $\mathbf{1}\{q_j > K_j\}$ 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.

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 and 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 C** for details):

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

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 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.[8] 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.[9] 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.

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

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

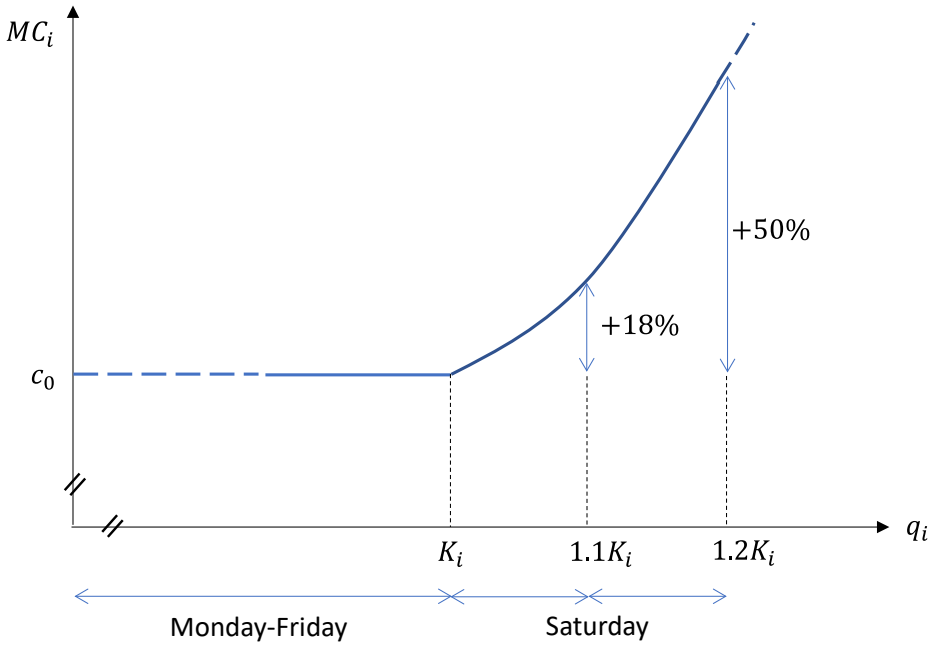
Table 2. Model Parameter Calibrations

Variable	Definition	Calibrated value	Units
α	Producer price sensitivity	79.27	(unitless)
b	Wholesale beef price	3.977	\$/lb
c_0	Base marginal cost	0.3897	\$/lb
γ	Marginal cost coefficient above threshold	2.1785	\$/lb
λ	Marginal cost curvature above threshold	1.5	(unitless)
$t(d_{jn})$	Per-unit transportation cost function	$\frac{4.0583\text{e-}4 \times d_{jn}}{1-\sigma(d_{jn})}$	\$/lb, d_{jn} in miles
$\sigma(d_{jn})$	Shrink factor function	$0.01 + 2.5\text{e-}4 \times \min\{d_{jn}, 100\}$	(unitless), 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.

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**.

Figure 3. Marginal Processing Costs and Capacity Constraints



Note: 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.

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 described above, we jointly adjust α and c_0 until the model

equilibrium reflects these values. This results in a value for α of 79.27 and a value for c_0 of 0.3897 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 $\bar{x}_{jn}$, 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, $\bar{s}_{jn}$, $j = 1, \dots, J$ and $n = 1, \dots, N$. Thus, in this equilibrium, the quantity of cattle procured by plant j from county n is equal to $\bar{s}_{jn}Q_n$. We assume a fixed portion of this quantity will be pre-committed supplies in the baseline equilibrium. That is, we assume $\bar{x}_{jn} = \varphi_r \bar{s}_{jn} Q_n$, where φ_r is the regional contracting share discussed in **Appendix B**.

4.5. Computation of Equilibria

Given the model parameterized as described above, we compute the set of Bertrand-Nash equilibrium prices p^*_{jn}, where $j = 1,2, \dots, J$ denotes plants and $n = 1, \dots, N$ denotes counties. The model explicitly considers 43 plants, owned by 22 firms, with cattle supplies coming from 1,993 counties in 39 states. We assume that plants do not compete for cattle from counties more than 650 miles away. 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.[10] See **Appendix D** for details.

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 1,993 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

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

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

To characterize the "markdown" concept that applies to this setting, 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 a set of plant-level processing activity $q_j(\mathbf{p}^*)$. Let the baseline equilibrium marginal costs for each plant j be $c(q_j(\mathbf{p}^*))$. 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., $\bar{x}_{jn} = 0,\ j = 1, \dots, J; n = 1, \dots, N$). 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 "breakeven" prices, p_{jn}^{be}. Plant j's breakeven price in county n, defined as $p_{jn}^{be} = b - c\left(q_j(\mathbf{p}^*)\right) - t_{jn}$, corresponds to the maximum price that plant j could offer on a marginal head of cattle from county n without incurring negative marginal profit.

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

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

Thus, 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, $\mu_{jn}^{multi} = p_{jn}^{ind} - p_{jn}^{nc}$, 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 $v_{jn} = \left(b - c_0 - t_{jn}\right) - p_{jn}^{be}$, 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 markdowns are modest yet potentially economically significant—the national average is \$3.32/cwt, or about 2.3% of the national average fed cattle price. About 56% of the markdown, \$1.87/cwt, can be attributed to the spatial configuration of plants. The use of AMAs in the market accounts for 39% of the full markdown, while only the remaining 5% of the markdown is due to firms' ownership of multiple plants.

Beyond the markdown, binding capacity constraints in the industry lower equilibrium prices by $0.95/cwt.

As shown in **Table 3**, the same patterns largely hold for each of the top five cattle producing states individually. In Kansas, a relatively high contracting markdown is offset by a relatively low spatial markdown to bring the full markdown just below the national average. In Nebraska and Iowa, where AMA usage is below national average (see **Appendix B**), markdowns are lower than average due to low contracting portions of the markdown. The opposite is true in Texas and Colorado, where relatively high AMA usage leads to higher than average contracting markdowns and full markdowns.

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 full markdowns, driven by the spatial component, are generally higher in the counties surrounding large and relatively isolated plants. 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, and in Colorado, where AMAs are used in 93% of 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.

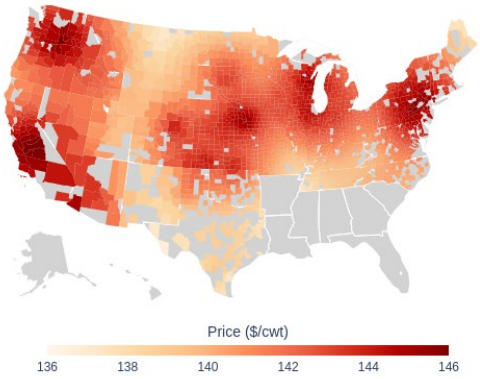
Table 3. Fed Cattle Prices and Markdowns in the Baseline Equilibrium

			Markdown Decomposition					
	U.S. Fed Cattle Share (%)	Price ($/cwt)	Full (%)	Full ($/cwt)	Spatial ($/cwt)	Multi-plant ($/cwt)	Contract ($/cwt)	Capacity Effect ($/cwt)
Full U.S.	100%	142.66	2.3%	3.31	1.88	0.17	1.27	0.95
Top 5 cattle producing states								
Kansas	22.0%	143.46	2.3%	3.26	1.61	0.22	1.42	0.88
Nebraska	20.4%	143.53	2.0%	2.86	1.74	0.15	0.96	1.05
Texas	19.6%	140.70	3.2%	4.52	1.81	0.15	2.57	1.16
Colorado	7.7%	143.04	2.4%	3.46	1.90	0.17	1.40	0.63
Iowa	7.4%	143.07	1.9%	2.72	1.83	0.13	0.77	1.28

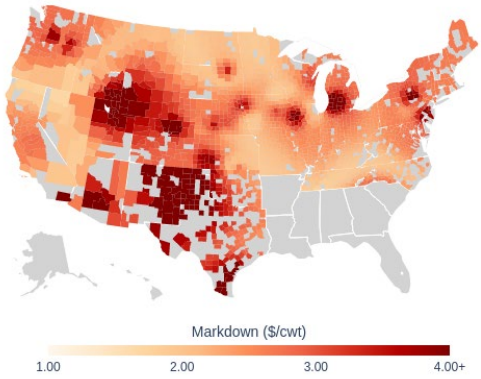
Note: The baseline equilbrium is computed with the model calibrated to the 2022 data. Results are converted to and presented in units of $/cwt.

Figure 4. County-level Price and Markdowns

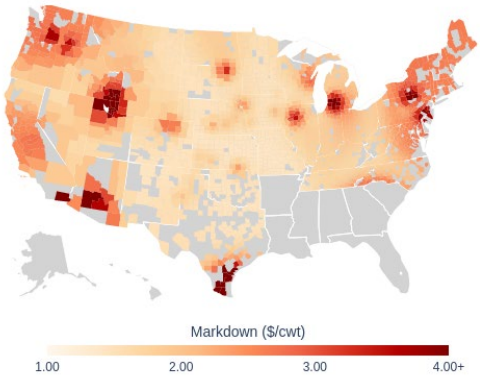
(a) Fed Cattle Price



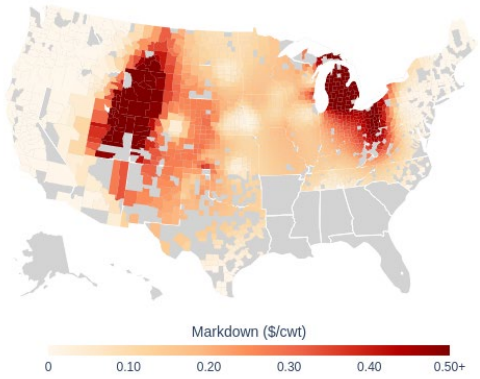
(b) Full Markdown



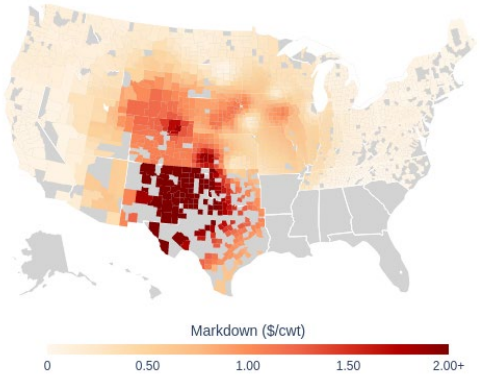
(c) Spatial Markdown



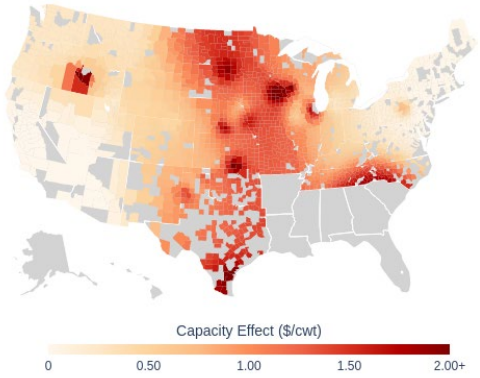
(d) Multi-plant Markdown



(e) Contracting Markdown



(f) Capacity Effect



Note: 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), (d), and (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 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 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 is much applied work (Graubner, Salhofer, and Tribl 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, 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 4**. These results align with expectations—the mill price formulation yields less competitive outcomes than the price discrimination setup. Average prices to feedlots (net of transportation costs) are nearly $3/cwt lower than under local price competition. The full markdown is about 45% higher with mill

pricing than with price discrimination. This is driven by 85% higher spatial markdowns under mill pricing, with the multi-plant and contracting portions of the markdown slightly lower than in the baseline model. Prices are also driven lower by the effect of capacity constraints, which is nearly 50% higher than in the baseline.[11]

There is interesting spatial heterogeneity in comparing the baseline model to the mill price model. Compared to the baseline, the mill price markdown is around 50% higher in Nebraska and Iowa, around 20% higher in Texas and Colorado, and 8% higher in Kansas. These results are all driven by significant increases in the spatial portion of the markdown in each state, while the other two portions of the markdown typically decrease modestly.

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, Murphy, and Scheinkman 1994). This is motivated by widely-held beliefs that the cattle cycle may yet have profound effects on market outcomes. For example, Crespi, Xia, and Jones (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 and 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, e.g., Nevo 2001), 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.

[11] 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.

Table 4. Fed Cattle Prices and Markdowns in the Mill Price Equilibrium

			Markdown Decomposition					
	U.S. Fed Cattle Share (%)	Price[a] ($/cwt)	Full (%)	Full ($/cwt)	Spatial ($/cwt)	Multi-plant ($/cwt)	Contract ($/cwt)	Capacity Effect ($/cwt)
Full U.S.	100%	139.79	3.5%	4.84	3.46	0.14	1.24	1.40
Top 5 cattle producing states								
Kansas	22.0%	142.56	2.5%	3.52	2.19	0.22	1.11	1.07
Nebraska	20.4%	141.45	3.0%	4.21	2.88	0.07	1.26	1.21
Texas	19.6%	138.56	4.0%	5.59	3.69	0.09	1.81	1.94
Colorado	7.7%	140.53	3.0%	4.15	3.00	0.23	0.93	1.84
Iowa	7.4%	140.53	3.0%	4.26	3.28	0.04	0.94	1.86

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.

The next scenario focuses on the controversial role of AMAs (Anderson, Mitchell, and McKenzie 2022; Garrido et al. 2022). As noted above, our baseline model includes pre-committed supplies in 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, Lusk, and Schroeder (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 2,000 head-per-day capacity in Glenwood, Iowa. This scenario was chosen due to the planned construction of a 2,000 head-per-day plant in Glenwood by Cattlemen's Heritage Beef Company. 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 would have impacted the market in 2022.

(f) ***Plant exit scenario***: We model the exit from the market of Tyson's 6,000 head-per-day plant in Holcomb, Kansas. This scenario parallels the shutdown of this plant for several months, due to a fire, in late 2019. However, we again note that we are not analyzing the actual event. Instead, we examine market outcomes had the plant had exited the market for all of 2022.

6.2 Counterfactual Results

Table 5 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 $3.44/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 $0.57/cwt decrease in the impact of capacity constraints compared to the baseline. Thus, prices decrease by more in the 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. In both scenarios, the full markdown decreases by about 20% compared to the baseline. In the independent plants scenario, this decrease is driven by decreases in both the multi-plant and contract components of the markdown. In the limited contracting scenario, the contract portion of the markdown accounts for the decrease. However, because the markdown is small relative to the fed cattle price in the baseline, the average fed cattle price increases by less than 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 $0.22/cwt increase in the average fed cattle price. On the other hand, the exit of the Tyson plant in Holcomb, Kansas more than doubles the capacity effect on prices, leading to a $1.31/cwt drop in the average fed cattle price. Note once again the asymmetry of these results—the exit of the 6,000 head per day Holcomb plant has about six times the price impact as the entry of the 2,000 head per day Glenwood plant.

Table 5. 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	2.3%	3.32	1.87	0.16	1.29	0.95
Supply Increase	89.21	3.7%	3.26	1.79	0.20	1.27	4.39
Supply Decrease	193.14	1.7%	3.31	1.96	0.13	1.22	0.37
Independent Plants	143.75	1.8%	2.62	1.90	0.00	0.72	0.72
Limited Contracting	143.93	1.8%	2.60	1.97	0.13	0.50	0.83
Plant Entry	142.89	2.3%	3.26	1.85	0.15	1.26	0.78
Plant Exit	141.35	2.4%	3.33	1.88	0.17	1.28	2.08

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.

7. Discussion and Preliminary Conclusions

The issue of market power in the beef packing industry has come under increasing scrutiny in recent years due to the rising 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 this rising price spread has focused on the exercise of market power by the packing plants, with some particular focus on the use of AMAs in the industry and firms' ownership of multiple plants.

In this paper, we show that in our calibrated Bertrand-Nash model of cattle procurement competition, price "markdowns"—the hallmark of buyer power—are relatively modest. In the baseline, the estimated markdown is $3.32/cwt, or about 2.3% of cattle prices. Most of the markdown (about 60%) 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 hasten to note, at this juncture, that the extent of model-estimated markdowns appears modest as a fraction of cattle prices. The impact of such markdowns on feedlot profits, of course, could nonetheless be economically significant.

Some caveats are clearly in order, as the parameterization of the model we developed inevitably requires assumption about difficult-to-observe relations (e.g., plant-level cost functions). Some concerns may be allayed by careful robustness exercises. 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 60% 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, 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%. While this reduction in concentration reduces the markdown by around 20%, we find only a very marginal increase in the fed cattle price.

Finally, our model suggests that capacity constraints may play a larger role in the rising spread between beef and cattle prices than either AMAs or multi-plant ownership. The importance of capacity constraints in the beef packing industry has been acknowledged previously, but not analyzed directly. Furthermore, the rising price spreads beginning in 2015 coincided with a shift from a decreasing to increasing trend in cattle slaughter. This study furthers the analysis by incorporating capacity constraints into a structural, spatially-explicit model of the industry. We find that 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.

The results of this paper are predicated on the presumption that beef packing firms compete in prices, and we model price determination in a Bertrand-Nash oligopsony framework for differentiated products. Whether the postulated form of conduct of packing firms is appropriate may be debatable. 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. A limited form of (possible) collusion concerns the use of mill prices. Indeed, we show that equilibrium in such a scenario entails larger markdowns, and higher profits for the packing firm, relative to the price discrimination formulation. That some collusion would be required for the effective use of mill prices is a direct consequence of the results in Thisse and Vives (1988).

More general questions about collusion (e.g., Hatfield and Lowery 2023) may be of interest, but are beyond the scope of the current paper. One way to assess the potential for collusion in our model might be by introducing 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 related but distinct question relates on the impacts of market power on consumer welfare, and how this is mediated by the relation between packers and the retail sector. These are matters we are currently investigating and may benefit from future work.

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APPENDIX A. Determining annual operating capacity

Capacity constraints play a key role in the model, and we pay special attention to capturing them correctly. We assume that each plant j has an operational capacity K_j that represents the maximum amount of cattle they can slaughter before marginal costs begin to rise. The capacities in our dataset are measured units of head per day. Converting these figures into annual operational capacities requires two pieces of information. First, we need to know how many days per year the plant can operate before capacity constraints begin to bind and costs start to rise. Second, we assume that these daily capacity numbers are physical capacities of the plants that may exceed their operational capacities. We therefore need to determine at what level of daily physical capacity utilization costs start to rise.

We answer both questions using the USDA AMS Actual Slaughter Under Federal Inspection report.[12] This report contains the daily total number of cattle slaughtered at federally inspected facilities. The report data from 2022 reveals a clear distinction between typical weekday slaughter and typical weekend (Saturday) slaughter, as illustrated in **Table A1**. We assume that the lower Saturday slaughter totals are due to higher marginal costs involved in Saturday operation, such as paying overtime wages to labor. We therefore conclude that capacity constraints begin to bind when the plant operates more than five days per week, or 260 days per year (5 days per week × 52 weeks per year).

To understand whether operational capacity constraints begin to bind before the daily physical capacity constraint is met, we turn to the distribution of daily slaughter totals on non-holiday weekdays, as shown in **Figure A1**. The modal daily slaughter occurs in the 97,000 – 98,000 head per day range. We assume that slaughter clusters around this point because it represents the daily operational capacity of the industry. We take the midpoint of the range, 97,500, as the daily operational capacity of the industry.

We combine the inferences we make from **Table 1** and **Figure 1** to convert our daily physical capacity values from CBW and market and news reports into annual operational capacity values that represent the point at which the plants' marginal costs begin to increase. The daily physical capacity of the industry in our dataset is 105,700 head per day. Guided by Figure 1, we assume that each plant's daily operational capacity is equal to 97,500/105,700 = 92.2% of its daily physical capacity. Then, following **Table 1**, we multiply this daily operational capacity by 260

[12] This report changed formats during 2022. For January – November 2022 data, see report ID SJ_LS711 (https://mymarketnews.ams.usda.gov/viewReport/3206). For December 2022 data, see report ID AMS_3658 (https://mymarketnews.ams.usda.gov/viewReport/3658).

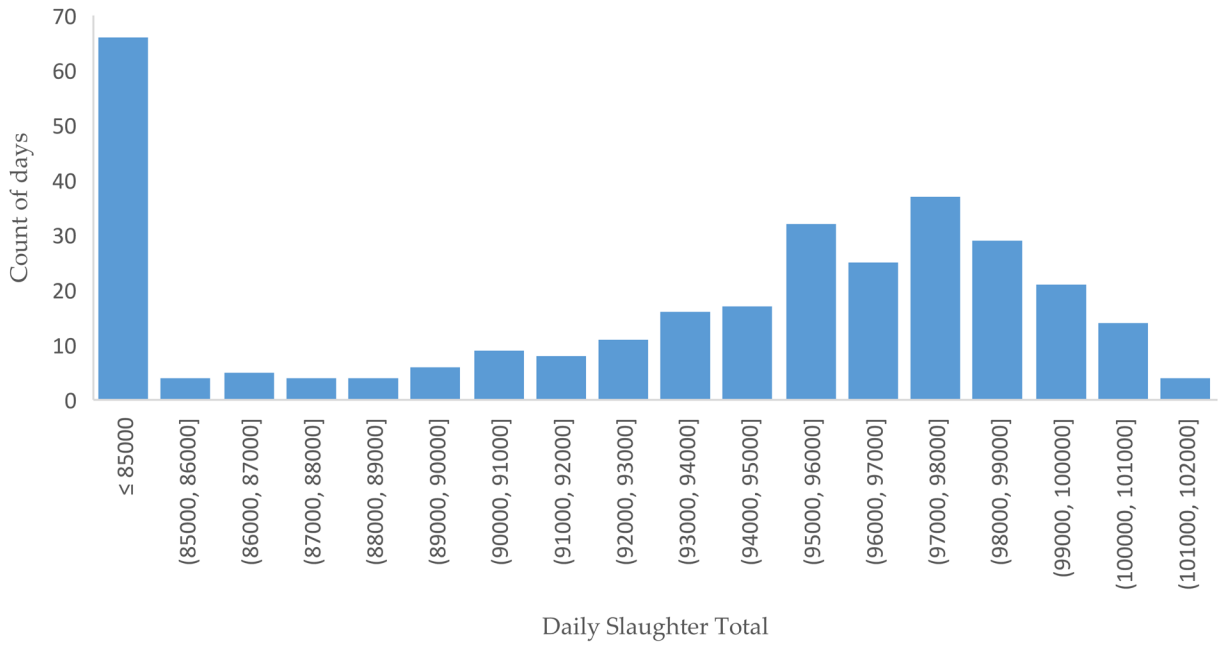
full operating days per year to get each plant's annual operational capacity. This results in a total adjustment of multiplying each plant's daily physical capacity by 0.922×260=240.

Table A1. Average 2022 Slaughter by Day of Week.

Day of Week	Average Daily Slaughter (head)
Monday	87,568
Tuesday	97,704
Wednesday	95,865
Thursday	93,321
Friday	91,979
Saturday	35,396

Note: Data from USDA AMS Actual Slaughter Under Inspection report (SJ_LS711 and AMS_3658.

Figure A1. 2022 Daily Weekday Slaughter



Note: This figure shows a histogram of daily slaughter totals from non-holiday weekdays in 2022. Data from USDA AMS Actual Slaughter Under Inspection report (SJ_LS711 and AMS_3658.

APPENDIX B. Regional contract shares and average prices

B1. Region Definitions and Contract Shares

We use several USDA Livestock Mandatory Reporting (LMR) reports to define sub-national regions and determine the contracting share in each region. The LM_CT142 is a weekly report covering the continental United States. The LM_CT142 reports that AMAs, defined as both formula contracts and forward contracts, accounted for 70% of fed cattle sales volume in 2022. This report also contains the total slaughter volume for each of 10 U.S. regions, but the report does not include the contract shares at the region level.

To get a reasonable estimate of the region-level contract shares, we next use the LM_CT151, which reports the volume of cattle purchased via contracts each week for each of the 10 U.S. regions defined in the LM_CT142. However, due to some redacting for confidentiality reasons, the total contract volumes from the LM_CT151 divided by the total slaughter volumes in the LM_CT142 results in a national contract share of only 64%, a non-negligible difference from the true value of 70%.

To remedy this, we next obtain region-level negotiated (spot-market) volumes from the following reports: LM_CT156 (TX-OK-NM), LM_CT157 (KS), LM_CT158 (NE), and LM_CT154 (all other regions). We add these region-level negotiated volumes to the region-level volumes from the LM_CT151, and subtract the total from region-level total slaughter volume in the LM_CT142. This result gives us an estimate of how much volume is missing due to redaction in the more detailed reports. We assign two-thirds of this missing volume to contract purchases and one-third of the missing volume to negotiated purchases. While this procedure is admittedly somewhat rough, it results in a national average contract share of 69%, which aligns well with observed national average in the LM_CT142.

The 10 regions used in these reports and the volume of fed cattle sales via contracts and in total, for 2022, are shown in **Table B1**.

Table B1. Regions and Contracting Shares

Region	States in Region	Contract Volume	Total Volume	Contract Share
TX/OK/NM	TX, OK, NM	4,339,810	5,061,908	86%
Kansas	KS	3,677,371	5,231,064	70%
Nebraska	NE	2,899,022	4,654,975	62%
Colorado	CO	1,689,047	1,819,882	93%
Western Cornbelt	IA, MN, MO	944,279	2,537,337	37%
Western States	AZ, CA, NV, UT, WA, OR, ID	965,747	1,132,129	85%
Northcentral/ East Mountain	WY, MT, SD, ND	212,568	649,627	33%
Eastern Cornbelt	WI, IL, MI, IN, KY	235,605	576,412	41%
Northeastern States	OH, PA, NY, WV, VA, CT, DE, ME, MA, MD, NH, NJ, RI, VT	150,086	268,398	56%
Southeast	AR, LA, TN, MI, AL, NC, SC, GA, FL	5,605	8,407	67%
Total		15,119,140	21,940,139	69%

B2. Average Prices

The USDA Contract Library has data on the source of the base price used in contracts. About 75% of all contracts reported to the USDA use one of the USDA Livestock Mandatory Reporting (LMR) cattle price reports as the base price. Of that 75%, the breakdown of the specific USDA reports used for the base price is as in **Table B2**.

Table B2. USDA Reports Used for Base Prices

USDA Report Title	% Reports
Nebraska Weekly Direct Slaughter Cattle – Negotiated Purchases (LM_CT158)	37%
Kansas Weekly Direct Slaughter Cattle – Negotiated Purchases (LM_CT157)	34%
TX-OK Weekly Direct Slaughter Cattle – Negotiated Purchases (LM_CT156)	23%
5 Area Weekly Weighted Average Direct Slaughter Cattle (LM_CT150)	5%
IA-MN Weekly Direct Slaughter Cattle – Negotiated Purchases (LM_CT167)	1%

The term "5 Area" in these reports refers to the five areas of:

1. Texas-Oklahoma
2. Kansas
3. Nebraska
4. Colorado
5. Iowa-Minnesota

Because the Contract Library is a pilot program and reporting to it is voluntary, we use the numbers in **Table B2** as a rough guide for determining which areas to use for calculating average prices; we do not necessarily try to match these numbers exactly in the model.

Note that in **Table B1**, TX, OK, and NM form one region, while in **Table B2**, the region is just TX and OK. Similarly, IA, MN, and MO form one region in Table B1, but in **Table B2** the analogous region is just IA and MN. To keep things consistent, we use the region definitions in **Table B1** when computing average prices. For example, we include NM with TX and OK even though the price report appears to cover only TX and OK. There are not may fed cattle in NM or MO (less than 1% of the national supply comes from these two states combined), so this shouldn't make any important difference to the results.

Following the guidance of **Table B2**, we assume that the 10 regions defined in **Table B1** compute their average prices over the areas listed in **Table B3**. The reasoning for these choices is as follows. Since the TX-OK, Kansas, and Nebraska price reports account for the majority of base prices, we assume that all transactions in these states (plus NM) use their individual regional average price for contracts. Since Colorado and the Western Cornbelt are in the 5 Area region, but the Colorado and IA-MN price reports account for very few contract base prices, we assume that these states use the whole 5 Area region to compute the average price. For the remaining five regions, which account for less than 20% of the total supply of fed cattle, there are not any regional price reports that could be used, so we assume that they use the national average price.

Table B3. Average Price Areas by Region

Region	Area used to compute average price
TX/OK/NM	TX/OK/NM
Kansas	Kansas
Nebraska	Nebraska
Colorado	5 Area*
Western Cornbelt	5 Area*
Western States	Entire U.S.
Northcentral/ East Mountain	Entire U.S.
Eastern Cornbelt	Entire U.S.
Northeastern States	Entire U.S.
Southeast	Entire U.S.

* "5 Area" is defined as above, but with NM and MO included.

Using these assumptions and the contracting shares in **Table B1**, the share of contracts in the model that use each area to compute their average price is as in **Table B4**.

Table B4. Share of contracts using each area to compute average price in the model

Area	Share of contracts
TX/OK/NM	32%
Kansas	27%
Nebraska	20%
5 Area*	15%
Entire U.S.	7%

* Including NM and MO.

The numbers in **Table B4** obviously do not match up **Table B2**. Nevertheless, the numbers in **Table B4** are fairly reasonable, and the process to obtain them is transparent. We therefore use the information in **Table B1** to compute each county's contracting share in the model. We then use the areas in **Table B3** when computing the regional average price that enters into firms' profit maximization.

APPENDIX C. 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:

$$\frac{\partial \Pi_f(\mathbf{p})}{\partial p_{jn}} = M_n\left[-s_{jn}(\mathbf{p}_n) + \sum_{k\in\mathcal{J}_f}\frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}(b - t_{kn} - p_{kn})\right] - \sum_{k\in\mathcal{J}_f}\frac{\partial C(q_k(\mathbf{p}))}{\partial q_k}\frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}M_n - \frac{\partial \bar{p}_r(\mathbf{p})}{\partial p_{jn}}\sum_{\ell\in r}\sum_{k\in\mathcal{J}_f}\bar{x}_{k\ell} = 0 \tag{C1}$$

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 $\mathbf{1}\{q_j > K_j\} = 1$ the marginal cost is:

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

Hence, if $c(q_k)$ denotes the marginal cost function as given in equation (5) in the text, then the condition in (C1) can be stated as:

$$M_n\left[-s_{jn}(\mathbf{p}_n) + \sum_{k\in\mathcal{J}_f}\frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}}\big(b - c\big(q_k(\mathbf{p})\big) - t_{kn} - p_{kn}\big)\right] - \frac{\partial \bar{p}_r(\mathbf{p})}{\partial p_{jn}}\sum_{\ell\in r}\sum_{k\in\mathcal{J}_f}\bar{x}_{k\ell} = 0 \tag{C2}$$

APPENDIX D. Computation of Equilibria

In this appendix we provide some details on the utilization of the Morrow and Skerlos' (2010) algorithm in the context of an oligopsony model of differentiated products. For notational clarity we focus on the case where the 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:

$$\text{(D1)} \qquad -s_{jn}(\mathbf{p}_n) + \sum_{k \in J_f} \frac{\partial s_{kn}(\mathbf{p}_n)}{\partial p_{jn}} \left(b - p_{kn} - m_{kn} \right) = 0 \quad , \quad \forall j \in J_f , \quad \forall f , \quad \text{and} \quad n = 1,2,...,N$$

where $m_{k\ell} \equiv c_0 + t_{k\ell}$ denotes the "total" marginal costs, that is, inclusive of processing costs and transportation costs. Note that there are $J \times N$ equations, which define the firms' best response functions, and solve 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, i.e., with elements $S_{ji} \equiv \partial s_{jn}(\mathbf{p}_n) \big/ \partial p_{in}$, 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 (D1) can then be expressed in matrix form as:

$$\text{(D2)} \qquad \mathbf{s}(\mathbf{p}_n) - \mathbf{\Omega}(\mathbf{p}_n) \left[b\boldsymbol{\iota} - \mathbf{m}_n - \mathbf{p}_n \right] = 0$$

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 $\mathbf{\Omega}(\mathbf{p}_n)$, relative to the standard demand/oligopoly case].

D.1. Oligopsony Nash equilibria with the η −FPI procedure

The fixed-point iteration to compute the Nash equilibrium commonly used in oligopoly models (e.g., Nevo 2011), which is labeled η −FPI by Morrow & Skerlos (2010) and Conlon & Gortmaker (2020), can readily be adapted to our oligopsony context. Specifically, from (D2) the Nash equilibrium can be expressed as:

(D3) $\mathbf{p}_n^* = (b\boldsymbol{\iota} - \mathbf{m}_n) - \boldsymbol{\Omega}^{-1}(\mathbf{p}_n^*)\mathbf{s}(\mathbf{p}_n^*)$

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 (D3):

(D4) $\mathbf{p} = \mathbf{c} + \boldsymbol{\eta}(\mathbf{p}) \quad , \qquad \boldsymbol{\eta}(\mathbf{p}) \equiv \boldsymbol{\Omega}(\mathbf{p})^{-1}\mathbf{s}(\mathbf{p})$

The algorithm computes $\mathbf{p}_n^i = (b\boldsymbol{\iota} - \mathbf{m}_n) - \eta(\mathbf{p}_n^{i-1})$ at each iteration, with an arbitrary initial $\mathbf{p}_n^0$. The fixed-point iteration proceeds until the first-order conditions are satisfied, that is until $\left\| \mathbf{foc}(\mathbf{p}_n^i) \right\| < tol$, where $\mathbf{foc}(\mathbf{p}_n^i) \equiv \mathbf{s}(\mathbf{p}_n^i) - \boldsymbol{\Omega}(\mathbf{p}_n^i)\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n^i \right]$ is the vector of first-order-conditions evaluated at the ith iteration, and tol is a preset tolerance level (e.g., $tol = 10^{-8}$).

D.2. Oligopsony Nash equilibria with the ζ −FPI procedure

Alternatively, to adapt the more efficient Morrow-Skerlos (2010) fixed point algorithm to our oligopsony case, we start with the decomposition $\mathbf{S}(\mathbf{p}_n) = \boldsymbol{\Lambda}(\mathbf{p}_n) - \boldsymbol{\Gamma}(\mathbf{p}_n)$, which here implies $\boldsymbol{\Omega}(\mathbf{p}_n) = \left[\boldsymbol{\Lambda}(\mathbf{p}_n) - \mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n) \right]$. Substituting this decomposition into (D2) yields

(D5) $\mathbf{s}(\mathbf{p}_n) + \boldsymbol{\Lambda}(\mathbf{p}_n)\mathbf{p}_n - \boldsymbol{\Lambda}(\mathbf{p}_n)(b\boldsymbol{\iota} - \mathbf{m}_n) + \left[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n) \right]\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n \right] = 0$

from which we get

(D6) $\mathbf{p}_n = (b\boldsymbol{\iota} - \mathbf{m}_n) - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\left[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n) \right]\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n \right] - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n)$

This is the basis for the Morrow-Skerlos (2010) ζ −FPI procedure:

(D7) $(b\boldsymbol{\iota} - \mathbf{m}_n) - \zeta(\mathbf{p}_n) \mapsto \mathbf{p}_n \quad , \quad \zeta(\mathbf{p}_n) \equiv \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\left[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n) \right]\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n \right] + \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n)$

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:

(D8)
$$(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n - \zeta(\mathbf{p}_n) =$$
$$(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\left[\mathbf{H} \circ \boldsymbol{\Gamma}(\mathbf{p}_n) \right]\left[(b\boldsymbol{\iota} - \mathbf{m}_n) - \mathbf{p}_n \right] - \boldsymbol{\Lambda}(\mathbf{p}_n)^{-1}\mathbf{s}(\mathbf{p}_n)$$

such that:

$$
\begin{aligned}
\boldsymbol{\Lambda}(\mathbf{p}_n)\left[(b\boldsymbol{\iota}-\mathbf{m}_n)-\mathbf{p}_n-\boldsymbol{\zeta}(\mathbf{p}_n)\right] &= \left[\boldsymbol{\Lambda}(\mathbf{p}_n)-\mathbf{H}\circ\boldsymbol{\Gamma}(\mathbf{p}_n)\right]\left[(b\boldsymbol{\iota}-\mathbf{m}_n)-\mathbf{p}_n\right]-\mathbf{s}(\mathbf{p}_n) \\
&= \boldsymbol{\Omega}(\mathbf{p}_n)\left[(b\boldsymbol{\iota}-\mathbf{m}_n)-\mathbf{p}_n\right]-\mathbf{s}(\mathbf{p}_n) \\
&= \mathbf{foc}(\mathbf{p}_n)
\end{aligned}
\tag{D9}
$$

Hence, the ζ −FPI , for our oligopsony case, terminates when

$$
\left\|\boldsymbol{\Lambda}(\mathbf{p}_n^i)\left[(b\boldsymbol{\iota}-\mathbf{m}_n)-\mathbf{p}_n^i-\boldsymbol{\zeta}(\mathbf{p}_n^i)\right]\right\| < tol \tag{D10}
$$

Conlon and Gortmaker (2020, footnote 65) note a similar termination rule for the standard demand case.