The Geographic Footprint of U.S. Dairy Policy

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Abstract

Many countries support dairy farms through government intervention in domestic dairy markets and border protection. This paper develops a spatial model of the U.S. dairy supply chain to investigate the effects of longstanding milk pricing rules enforced by the eleven Federal Milk Marketing Orders (FMMOs) on the geography of milk production and processing, inter-regional farm milk shipments, international trade, and welfare. While our simulation results comport with the standard finding that FMMOs transfer surplus from domestic beverage milk consumers to dairy farms, we find welfare effects to be small as a share of revenue, with notable regional differences. Upon removal of the regional pricing rules, production of farm milk falls across all marketing order regions, with the largest decline occurring in the Southwest (7%). Shipments of farm milk as a share of production increase slightly, indicating that policy-induced market distortions are not the source of what might appear as excessive inter-regional milk trade.

Keywords: supply chain, policy, trade, welfare

1 Introduction

To what extent do agricultural policies shape the geographic organization of agricultural and food production and the patterns of commodity trade? In developed countries such

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policies are often meant to benefit farm businesses (Gardner, 1987; Anderson, Rausser, and Swinnen, 2013), but at what cost to consumers and society, and how are these impacts distributed geographically? The present paper addresses these questions in the context of longstanding U.S. policies that regulate returns to dairy farming through classified milk pricing, a form of government-sanctioned third-degree price discrimination, and revenue pooling. The classified pricing system raises the price of farm milk when processed into beverage milk products, which are demanded less elastically than other dairy products owing to high transportation costs, while revenue pooling ensures that dairy farmers receive a uniform milk price.

Measuring and comparing the social costs of various farm programs is a staple of agricultural economics, with early contributions by Nerlove (1958), Wallace (1962), or Gardner (1983) still informing much of current research on the topic. These seminal works emphasized tradeoffs between farmer, consumer, and taxpayer welfare, while Floyd (1965) was among the first to analyze the incidence of price support programs on the returns to land and labor.

More recently, there has been growing interest in quantifying policy impacts that are difficult to capture within stylized welfare frameworks yet increasingly relevant to society, such as the effect of U.S. farm policy on obesity (Alston and Okrent, 2017), the impact of global agricultural policies on regional water resource depletion (Carleton, Crews, and Nath, 2024), the consequences of heat-induced agricultural policies on domestic and foreign interest groups (Hsiao, Moscona, and Sastry, 2025), or the influence of agricultural policies on crop location and climate vulnerability (Greyling, Pardey, and Senay, 2025). In that spirit, the present paper investigates the geographic footprint of U.S. dairy policy, that is, the extent to which the spatial organization of milk production and dairy product manufacturing and trade in the U.S. can be attributed to policy-driven market distortions, as opposed to natural factors, technology, and consumer preferences.

To this end, we develop and calibrate a spatial equilibrium model of the U.S. dairy supply chain tailored to address counterfactual questions related to milk pricing rules set by eleven Federal Milk Marketing Orders (FMMOs). These rules lie at the core of past and current U.S. dairy policy, with the latest round of amendments promulgated by the federal government in January 2025, following a consultation process that culminated in referenda held in each of the FMMOs.[1]

In terms of aggregate welfare, we find that FMMO pricing rules transfer surplus from U.S. consumers ($340 million per year) towards farmland owners ($83 million) but also foreign consumers of U.S. dairy products ($47 million). The four-fold difference in magnitude between the consumer loss and the producer-side gain is explained by the small share

[1] https://www.ams.usda.gov/content/usda-issues-final-rule-amendments-federal-milk-marketing-orders.

of the dairy product dollar accruing to cropland. The reason for the positive transfer to foreign consumers is that they benefit from lower prices of exportable manufactured dairy products other than beverage milk.

These impact estimates are small relative to the overall value of the dairy market. Nonetheless, they mask notable geographical reorganizations of milk production and processing after the hypothetical removal of FMMO pricing rules, notably a decrease in milk production in the Southwest, an increase in milk processing in the Mountain West and the Upper Midwest, and the split of a previously integrated farm milk market into two separate marketing zones.

A notable feature of the dairy supply chain is that farm milk, certain dairy products such as beverage milk, and dairy feed inputs such as corn silage are water-heavy and costly to transport, resulting in a spatially-scattered supply chain that reflects the size of regional consumer markets, in addition to comparative advantage in dairy feed crop production, farm milk productivity, and regional processing efficiency. Another factor contributing to the spatial distribution of dairy production may be the fact that some processed dairy products such as specialty cheeses can be differentiated by region of origin, limiting regional specialization.

FMMO pricing policies may act as another critical determinant of the geography of dairy production and inter-regional trade. For instance, a higher average price for farm milk in an FMMO region induced by classified pricing increases local milk production and attendant feed crop supply from local and other sources and encourages farm milk shipments into the region, distorting the geography of crop and milk production and trade. Indeed, our data indicate that 3.6% of the total value of farm milk in the U.S. is shipped outside of its production region; the Mountain West, which is not regulated by any FMMO, exports 5.5% of its farm milk to neighboring FMMO regions.

The effects of FMMO pricing rules on milk production, shipments of farm milk between regions, or the value of dairy product manufacturing might ideally be assessed by evaluating the change in each of these outcomes when changes to FMMO policy were implemented, controlling for the impacts of other factors that may have changed over time. However, since FMMO policies change infrequently, the effectiveness of this approach is limited. While policy reforms and consolidations of marketing order regions have occurred throughout the existence of the FMMOs, with substantial changes implemented in 2000 and a set of newly approved changes coming into effect this year,[2] the general structure of classified pricing and revenue pooling has remained unchanged since the 1930s. Ad-

[2]Milk in the Northeast and Other Marketing Areas; Uniform Pricing Formula Provisions, 90 Fed. Reg. 6600 (January 17, 2025) amending 7 CFR Parts 1000, 1001, 1005, 1006, 1007, 1030, 1032, 1033, 1051, 1124, 1126, 1131, and 1170.

ditionally, many other factors have changed since classified pricing and revenue pooling were introduced, including substantial changes to the dairy industry and secular changes in consumer demand.

Therefore, instead of relying on an elusive econometric exercise, we adopt a structural approach to evaluate the changes in outcomes of interest, including welfare, in a scenario where FMMO pricing rules are removed. Because the dairy policy we study has been in place for almost a century, we use observed data to calibrate a baseline equilibrium with explicit price distortions (Lucas Jr, 1976). Our counterfactual then replicates the competitive equilibrium that would prevail absent FMMO pricing rules.

Our model structure borrows from new quantitative trade models, as exemplified in Costinot, Donaldson, and Smith (2016), with important differences and innovations. Our focus on national and regional dairy policy impacts, rather than climate-induced global crop yield shocks, dictates a more parsimonious treatment of crops not directly used in dairy feed, a focus on inter-regional rather than global trade flows, and an explicit representation of crop transformation into farm milk, milk components,[3] and consumer dairy products. A relatively detailed modeling of the dairy supply chain, both geographically and vertically, is warranted because the policy we study consists of regionally-determined price distortions for milk components across industrial uses.

Specifically, the prices paid by manufacturers for milk components differ according to their end use, and these differences further vary depending on processing location. The general philosophy behind the policy-mandated price differentials is that component prices are set at higher levels for use in the production of fluid milk, whose local demand is relatively inelastic, than for use in more processed dairy products such as cheese or milk powder, which are traded on the international market. Milk producers receive a weighted-average price that partially reflects the higher price generated by fluid milk sales. Thus, the component price differentials are believed to raise farm milk prices above the competitive level, increasing the total supply of farm milk and attendant demand for dairy feed inputs while distorting the dairy product mix away from beverage milk (Kessel, 1967; Ippolito and Masson, 1978). In our model, classified pricing is reflected in a policy parameter that modulates the price paid for milk components depending on their end use.

We calibrate our model using recent regional data on dairy product shipments, farm milk shipments and utilization, and crop production and use from a variety of sources as well as a set of behavioral parameters drawn from the literature. Demand parameters include the elasticity of demand for dairy products and elasticities of substitution between dairy product categories and, within categories, between origin regions. A separate set of

[3]Milk derives its value from three solid components: butterfat, protein, and other solids (primarily lactose and trace minerals).

demand parameters is used for export demand. Supply parameters include a parameter reflecting the heterogeneity of regional crop yields and governing crop acreage elasticities, a parameter governing the intensive margin of crop supply, the elasticity of substitution across crops used in dairy feed, and elasticities of substitution across milk components in dairy product manufacturing.

Our counterfactual analysis of the removal of regional milk component price differentials delivers three main results. First, although nothing in our model structure forces these patterns, our calibration data is consistent with the commonly held view that the component pricing rules (i) shift the product mix away from beverage milk, (ii) result in higher prices received by dairy farmers for farm milk, and (iii) increase the prices paid by domestic consumers for dairy products. Specifically, upon removing the differentials the overall dairy price index for U.S. consumers decreases in all domestic regions as the consumer price of beverage milk decreases while the consumer prices of other dairy products increase. In contrast, foreign consumers are hurt as they do not consume beverage milk of U.S. origin. In all regions, cropland, the residual claimant of dairy production value, decreases in value.

Second, the overall magnitude of these effects is small relative to the size of the industry, revealing that the surplus transfer enabled by FMMO pricing rules, if present, has a low social cost. Removing these rules increases domestic welfare by a mere 0.12% relative to the overall value of the dairy market. More pronounced effects are found regionally. For instance, land rents decrease by 1.6% in the Northeast, which is responsible for 15% of domestic milk production value, and by 0.9% in the Southwest, which is responsible for 10% of domestic milk production value. The Southwest also experiences large decreases in milk production (-7.1%) and milk use (-4.9%). In contrast, farm milk utilization increases in the Unregulated region—part of the Mountain West—by 2.4% and, to a lower extent, in the Upper Midwest, indicating some geographical reallocation of milk processing. On the consumer side, increases in consumer surplus relative to the regional value of consumption do not exceed 0.7% in any U.S. region.

Third, one cannot conclude that longstanding FMMO pricing rules have resulted in increased shipments of farm milk across U.S. regions. Indeed, total milk shipments *increase* slightly upon removal of FMMO rules—by 0.08 percentage points, for a baseline share of production value shipped of 3.6%. To put this effect in perspective, we use our model to compute the minimum increase in milk transportation costs that would eliminate all inter-regional trade in farm milk, and find this value to be 74%. Thus, it would take a significant rise in transportation costs to stop the flow of farm milk from lower-cost production regions to higher-value use regions, and, in the aggregate, milk trade appears to be the result of market fundamentals, rather than an artifact of policy distortions. Still, in the counterfactual without FMMO pricing rules, our model predicts a geographic split of the farm milk market, which is fully integrated in the baseline due to inter-regional milk trade, into two separate spatial markets. One block would cover the area to the west of the Rocky Mountains and the other the rest of the U.S., as milk shipments from the Unregulated region would be greatly reduced. Qualitatively at least, U.S. dairy policy thus appears to have had an influence on the regional integration of farm milk markets.

Our analysis proceeds as follows. The next section describes the institutional setting. Sections 3, 4, and 5 are dedicated to model description, equilibrium definition, and parameter identification. Section 6 discusses the information used to determine model parameter values. Section 7 presents the results of our counterfactual exercise, including a sensitivity analysis along key shape parameters. Section 8 concludes.

2 Institutional setting

Since the passage of the Agricultural Marketing Agreement Act of 1937 (AMAA), the FMMOs have overseen sales of milk within regions comprising the majority of milk production and processing in the U.S. Marketing order pricing rules have two key elements: classified pricing and revenue pooling within marketing areas. The classified pricing system defines classes based on four end-use product categories and establishes minimum prices for milk used in those classes. This allows for price discrimination across end-use markets, as prices for beverage products, whose regional demand is less elastic, are set at higher levels. Regional demand for beverage milk products is less elastic due to the relatively high cost to transport beverage milk, which establishes natural limits on competition from beverage milk products manufactured in other regions. Gains from price discrimination are redistributed to farmers through regional revenue pooling, establishing a "blend price" received by farmers that deliver milk to processors within a marketing order region.

Milk buyers, known as "handlers" in the FMMO authorizing legislation and regulations, include those who minimally process milk into beverage products and those who produce more heavily processed manufactured dairy products. Handlers are the regulated entities under FMMO pricing rules and are obligated to pay the minimum class prices if participating in an FMMO. In other words, milk producers may choose to sell milk to a handler in any region, but if a handler is located in and regulated by a specific marketing order region, then they are required to pay the order-regulated prices. This creates an incentive for farm milk to be moved between regions if milk producers can receive a higher (regulated minimum) price in another region, despite high transportation costs for farm milk relative to manufactured dairy products.

2.1 Historical background

The origins of the current FMMO system lie in the actions of milk marketing cooperatives in the early 20th century (Nourse, 1962). Milk marketing was highly localized since the lack of refrigeration technology limited the distance that fresh milk could travel before spoiling. With many milk producers in a local region interacting with a small number of milk processors, the processors benefited from market power (Ippolito and Masson, 1978).

After the passage of the Capper-Volstead Act of 1922, agricultural cooperatives gained a degree of protection from antitrust challenges and marketing cooperatives emerged in the dairy industry (Erba and Novakovic, 1995). They began to implement a form of classified pricing by charging a higher price for milk used in beverage products than for milk used in manufacturing. Cooperative members would then receive a blend price based on the share of cooperative-managed milk used in beverage products. However, an independent dairy farmer could bargain directly with a milk handler to sell milk at a price below the cooperative-set beverage milk price but above the blend price, thereby increasing their own revenue to the detriment of the cooperative. Dairy farmers and producer cooperatives began calling for government intervention in the milk market due to the perceived concentration of bargaining power among milk handlers and the inherent instability of the cooperative-based classified pricing system.

After an original version was declared unconstitutional, the AMAA was passed in 1937 and is the permanent legislation that authorizes FMMOs to this day. The AMAA declares it the policy of Congress to "establish and maintain such orderly marketing conditions for agricultural commodities in interstate commerce" through the use of marketing agreements and marketing orders (7 U.S.C. §602(1)). The requirements for milk marketing orders outlined in the AMAA reflect the pricing practices previously implemented by dairy cooperatives. Milk marketing orders require that milk be classified according to its end use, that handlers face the same minimum prices for each classified use, and that producers receive a uniform price (7 U.S.C. §608(5)). Producers may request the creation of a marketing order in a specific marketing area and handlers are then presented with the proposed order language. Handlers may accept or reject the proposal, but even if the proposal is rejected the Secretary of Agriculture may still implement the order if a sufficient number of producers vote to move forward. Since producers hold the final decision over whether to implement the proposed order, the system provides a mechanism for milk producers to impose regulation on milk handlers (Kessel, 1967).

Additionally, the AMAA establishes that marketing orders should ensure "an orderly flow of the supply [of an agricultural commodity] to market throughout its normal marketing season to avoid unreasonable fluctuations in supplies and prices" (7 U.S.C. §602(4)). This policy has generally been interpreted as ensuring a regular supply of milk for use in beverage products. Early implementations of the milk marketing order requirements of classified pricing and uniform producer prices involved a two-price system, with a higher price established for milk used in beverage products and a lower price for milk used in more processed dairy products, also known as manufactured products. The higher price for milk used in beverage products ensured that demand for beverage milk products was met first, with any remaining milk used in manufactured products. The price for milk used in beverage products was determined by adding a location-based differential to the minimum price for milk used in manufactured products. The size of the differential was based on the location where the milk was delivered, with a lower differential in regions where milk production was high relative to quantity demanded and a higher differential in areas with greater populations and more demand for beverage milk products. This pricing structure further incentivized movement of farm milk from regions with lower milk production costs to regions with less milk production.

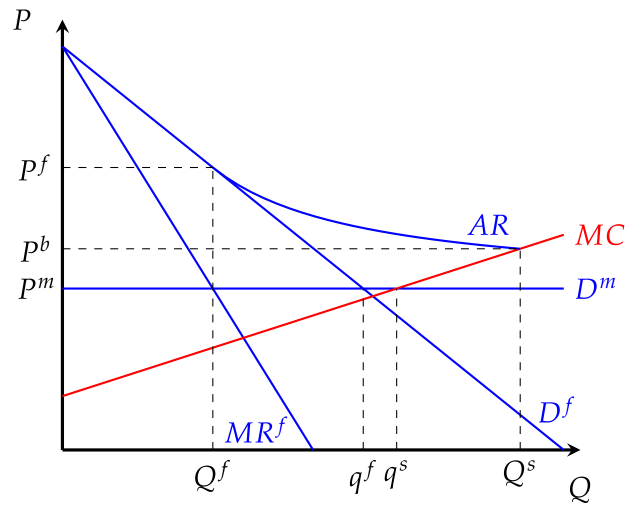
2.2 Canonical model of milk marketing order regulation

Kessel (1967) depicts a two-price system of classified pricing, reflecting the regulatory structure under early milk marketing orders. His model assumes that the local nature of the market for beverage milk results in downward-sloping demand while the national scope of the market for manufactured dairy products leads to infinitely elastic demand for manufacturing milk. Additionally, government purchase programs that were in effect at the time created support prices for major manufactured dairy products, which would be consistent with a demand function that is flat at the government support price.[4]

Figure 1 depicts Kessel's model of an individual milk marketing order. Two equilibrium conditions determine the total quantity of milk supplied to the market, Q^s, and the quantity of milk used in beverage (or fluid) milk products, Q^f. The first condition states that the equilibrium quantity of milk supplied is determined where the average revenue is equal to the marginal cost of milk production. The second condition states that at the optimal allocation of milk between beverage and manufacturing products, the marginal revenue in the beverage and manufacturing milk markets must be equal (if milk is processed into both end products), or all milk must be transformed into beverage products. The AR curve defines the blend price received by milk producers for any level of output and approaches the manufacturing demand curve asymptotically as the quantity processed into beverage milk remains constant at Q^f for large enough quantities of milk processed. The equilibrium

[4]The price support program for milk was originally authorized in 1949 and was implemented through government purchases of butter, cheese, and nonfat dry milk. The program was eliminated by the 2014 Farm Bill, but it had been non-binding since the mid-1990s as the milk price was consistently higher than the support price (Schnepf, 2014).

Figure 1: Model of a single federal milk marketing order from Kessel (1967)



Source: Authors' reproduction of Figure 1 from Kessel (1967).

blend price, P^b, is a weighted average of the price paid for beverage milk, P^f, and the price paid for manufacturing milk, P^m, and results in a greater quantity of milk supplied to the market than in the absence of classified pricing and revenue pooling ($Q^s > q^s$). Compared to the competitive equilibrium, less milk is available to consumers as fluid milk ($Q^f < q^f$) and more milk is used in manufacturing ($Q^s - Q^f > q^s - q^f$).

3 Structural model of the dairy supply chain

Our model includes three production stages: crop production, farm milk production, and dairy product manufacturing, related vertically through technological relationships. Feed crops compete with other crops for a fixed land base, may be used outside of the dairy sector, and are converted into milk through the feeding of dairy cows. We do not model the supply of animals explicitly. Instead, we assume that herd size adjusts to the regional availability of dairy feed and the derived demand for farm milk. Similarly, we assume that farm labor is supplied in a perfectly elastic fashion. Thus, our model is meant to capture long-run responses to policy, which is appropriate given the longstanding nature of the FMMO system.

Production, processing, and consumption are determined regionally and linked spatially through trade in dairy feed crops, farm milk, and dairy products. As the policy we study is spatial in nature, the geographic resolution of our model captures that of the

FMMOs, resulting in 11 regulated regions and a residual domestic region representing areas not under FMMO jurisdiction. Regions are labeled from 0 (for "rest of the world," hereafter ROW) to $I = 12$ using the indices i or j.

Trade includes international exports of feed crops and international imports and exports of dairy products.[5] We assume fixed prices for commodities traded internationally.[6] In our model, farm milk can only be traded between U.S. regions. Indeed, its high water content and the need for refrigeration make it very costly to transport, which explains why exports and imports of farm milk are negligible. Similarly, compared to the value of U.S. feed crop production and exports, the value of imported feed crops is very small, thus we simply subtract it from feed crop exports. In addition to trading farm milk, FMMO regions are allowed to trade feed crops (except dairy silage) and dairy products.[7]

3.1 Demand for dairy products

Dairy products are indexed by $n = 1, \ldots, N$. Trade in dairy products across U.S. regions and internationally is subject to iceberg trade costs $\tau_{ij}^n \geq 1$, where i is the origin region and j the destination region, and $\tau_{ii}^n = 1$. That is, in order for one unit of dairy product n to arrive in region j, region i needs to ship τ_{ij}^n units. Iceberg trade costs also define price relationships between trading regions, since the price of product n in region j that is shipped from region i must be equal to the cost of procuring τ_{ij}^n units, namely $\tau_{ij}^n p_i^n$, where p_i^n is the price of product n in region i.

Preferences in region $j \geq 1$ are represented by the following utility function:

$$U_j(C_j^0, C_j) = C_j^0 + \left(\beta_j\right)^{\frac{1}{\epsilon}} \frac{\left(C_j\right)^{1-\frac{1}{\epsilon}}}{1 - \frac{1}{\epsilon}} ,$$

where $\beta_j > 0$, $0 < \epsilon < 1$ is the (absolute) elasticity of demand for dairy, C_j is a dairy

[5]In what follows, the terms "exports" and "imports" systematically refer to international trade flows.

[6]Although the U.S. maintains tariff-rate-quotas (TRQs) on imported dairy products, the quotas themselves have not been binding in recent times. Beckman, Gale, and Lee (2021) show that imports are either well below the quota, or domestic prices are at or below border prices, indicating that imports are unconstrained by the quota, even if they are sensitive to the out-of-quota tariff.

[7]The overall structure of our dairy supply chain model is reminiscent of previous work by Cox and Chavas (2001), who specify a spatial equilibrium model with inter-regional trade in farm milk and dairy products. Key differences are that they do not model crop production and instead directly assume regional milk supply elasticities; they specify independent demands for dairy products whereas our regional demand functions are derived from utility maximization; they assume that dairy products are perfectly substitutable across origin regions; they do not model foreign demand for U.S. dairy products; they do not allow for substitution of milk components in dairy product manufacturing; and they apply price wedges at the level of dairy products, as opposed to directly modeling class-based component pricing. In terms of counterfactuals, they study the joint removal of FMMO pricing and the U.S. dairy price support program.

product aggregate, and C_j^0 represents consumption of non-dairy foods and other goods. Thus, utility is quasilinear and demand for dairy as a whole is inelastic. The dairy aggregate C_j is a nested constant-elasticity-substitution (CES) aggregate, with the outer nest defined across dairy products $n = 1, \ldots, N$ as

$$C_j \equiv \left[\sum_{n \geq 1} \left(\beta_j^n\right)^{\frac{1}{\kappa}} \left(C_j^n\right)^{\frac{\kappa-1}{\kappa}} \right]^{\frac{\kappa}{\kappa-1}} ,$$

where $\beta_j^n \geq 0$, $\sum_{n\geq 1} \beta_j^n = 1$, and $\kappa \in (0,1) \cup (1, \infty)$ represents the elasticity of substitution across products. The inner nest, C_j^n, serves to aggregate over regional origins of product n:

$$C_j^n \equiv \left[\sum_{i \geq 0} \left(\beta_{ij}^n\right)^{\frac{1}{\sigma^n}} \left(C_{ij}^n\right)^{\frac{\sigma^n-1}{\sigma^n}} \right]^{\frac{\sigma^n}{\sigma^n-1}} ,$$

with $\beta_{ij}^n \geq 0$, $\sum_{i\geq 0} \beta_{ij}^n = 1$, and $\sigma^n \in (0,1) \cup (1, \infty)$.

The elasticity of substitution across origins, σ^n, referred to as an Armington elasticity (Armington, 1969), is allowed to vary across products because for some products, e.g., cheese, the region of origin may be a meaningful differentiating attribute while for others, e.g., whey, products are likely to be more homogeneous. For the sake of parsimony we assume that elasticities are identical across consumption regions. We deem this restriction all the more acceptable as our regions are regions of the U.S., as opposed to world countries.

Demand for U.S. dairy products by the ROW follows a similar structure, with the exception that demand for dairy products of foreign origin is not modeled explicitly (and thus is assumed to be part of the ROW's numeraire). This is tantamount to ignoring both income effects and substitution effects (other than those amongst products of U.S. origin) on the part of the ROW.[8] We also allow for differing substitution and demand elasticities, denoted σ_0^n, κ_0, and ϵ_0, in addition to differing values of the share parameters.

Utility maximization implies the following demand in region $j \geq 1$ for dairy product n coming from region $i \geq 0$:

$$C_{ij}^n = \beta_j \beta_j^n \beta_{ij}^n \left(P_j\right)^{\kappa-\epsilon} \left(P_j^n\right)^{\sigma^n-\kappa} \left(\tau_{ij}^n p_i^n\right)^{-\sigma^n} ,$$

[8]If one were to introduce foreign consumption of foreign dairy products into the model, one would also need to introduce production of such products. Since the focus of this study is domestic U.S. dairy policy and its impacts on U.S. dairy production and welfare, the choice to abstract from world-level market-clearing mechanisms for dairy products of foreign origin seems appropriate.

where

$$P_j^n \equiv \left[\sum_{i\geq 0} \beta_{ij}^n \left(\tau_{ij}^n p_i^n\right)^{1-\sigma^n}\right]^{\frac{1}{1-\sigma^n}} \quad \text{and} \quad P_j \equiv \left[\sum_{n\geq 1} \beta_j^n \left(P_j^n\right)^{1-\kappa}\right]^{\frac{1}{1-\kappa}}$$

are CES price indices in region j for dairy product n and for all dairy products, respectively. Similarly, demand by the ROW for dairy product n originating from U.S. region $i \geq 1$ is

$$C_{i0}^n = \beta_0 \beta_0^n \beta_{i0}^n \left(P_0\right)^{\kappa_0 - \epsilon_0} \left(P_0^n\right)^{\sigma_0^n - \kappa_0} \left(\tau_{i0}^n p_i^n\right)^{-\sigma_0^n} \ ,$$

where

$$P_0^n \equiv \left[\sum_{i\geq 1} \beta_{i0}^n \left(\tau_{i0}^n p_i^n\right)^{1-\sigma_0^n}\right]^{\frac{1}{1-\sigma_0^n}} \quad \text{and} \quad P_0 \equiv \left[\sum_{n\geq 1} \beta_0^n \left(P_0^n\right)^{1-\kappa_0}\right]^{\frac{1}{1-\kappa_0}} \ .$$

We assume that the price of each dairy product sourced from international markets, p_0^n, is fixed. In contrast, the regional prices of U.S. dairy products, p_i^n $(i \geq 1)$, are determined endogenously.

3.2 Dairy product manufacturing and derived demand for milk components

Denote the quantity of dairy product n produced in region $i \geq 1$ as Q_i^n. Given trade costs, equilibrium in the dairy product market implies that

$$Q_i^n = \sum_{j\geq 0} \tau_{ij}^n C_{ij}^n \ .$$

Dairy products are manufactured by combining milk components such as fat, protein, and other solids with other inputs. These other inputs are assumed to have fixed prices and are represented as a single aggregate. The production function for dairy product n in region i is

$$Q_i^n = \min\left(Z_i^n, \frac{N_i^n}{\nu_i^n}\right) \ ,$$

where Z_i^n is the aggregate of milk components, N_i^n is the aggregate of other inputs, and ν_i^n thus represents the fixed amount of other inputs used per unit of output. Let milk components be indexed by $k = 1, \ldots, K$. The milk component aggregate is then defined as follows:

$$Z_i^n \equiv \left[\sum_{k\geq 1} \left(\gamma_i^{nk}\right)^{\frac{1}{\varsigma^n}} \left(Z_i^{nk}\right)^{\frac{\varsigma^n - 1}{\varsigma^n}}\right]^{\frac{\varsigma^n}{\varsigma^n - 1}} \ ,$$

where $\gamma_i^{nk} \geq 0$, $\sum_{k\geq 1} \gamma_i^{nk} = 1$, and $\varsigma^n \in (0,1) \cup (1,\infty)$ is the elasticity of substitution across milk components in the manufacturing of product n. While milk provides components in relatively fixed proportions, dairy manufacturing allows for substitution across components; our aggregates allow for differing component substitutability across dairy products.

In regions regulated by an FMMO, component prices are set according to the dairy product they are used to manufacture. Denoting v_i^k as the baseline price of component k in region i, $v_i^{nk} \equiv \delta_i^{nk} v_i^k$ is the regulated purchase price for component k when used in product n. Thus, $\delta_i^{nk} > 0$ represents the policy-driven price wedge between the "natural" price of component k in region i and its mandated price for use in dairy product n. As normalization, we set $\delta_i^{nk} = 1$ for butter and dry milk products, i.e., the Class IV uses according to the FMMO classification.

Cost minimization implies that the output-conditional demand for milk component k used in product n in region i is

$$Z_i^{nk} = Q_i^n \gamma_i^{nk} \left(V_i^n\right)^{\varsigma^n} \left(\delta_i^{nk} v_i^k\right)^{-\varsigma^n} , \tag{1}$$

where V_i^n is a CES price index representing the overall price of milk components used for product category n in region i, defined as

$$V_i^n \equiv \left[\sum_{k\geq 1} \gamma_i^{nk} \left(\delta_i^{nk} v_i^k\right)^{1-\varsigma^n}\right]^{\frac{1}{1-\varsigma^n}} .$$

We denote the fixed price of the other inputs by w.[9] The fixed-proportions dairy technology implies that the market price of dairy product n in region i exhausts its production cost, that is:

$$p_i^n = V_i^n + w\nu_i^n .$$

3.3 Use and trade of farm milk

Regional demand for milk components translates into derived demand for farm milk. Farm milk provides components in fixed proportions that are independent of the region of production and is a tradable commodity across U.S. regions; thus its availability in any given region is given by local production plus net shipments from other U.S. regions. Denoting by M_{ji} the quantity of milk from region j used in the manufacturing of dairy products in region i and by ζ^k the amount of component k present in one unit of farm milk,

[9]There is no benefit to allowing the price of the other inputs to depend on the region (or the dairy product for which they are used) since the input intensity ν_i^n is already region- and product-dependent.

we must have:

$$\sum_{n\geq 1} Z_i^{nk} \quad = \zeta^k \textstyle\sum_{j\geq 1} M_{ji} \quad \text{for all } k \geq 1 \,. \tag{2}$$

This set of equalities implies that in the processing region, the equilibrium product mix is such that all the milk components are exhausted. If not, the regional price of the leftover component would approach zero, and Equation (1) then implies that demand for that component across all dairy products in which it is used would increase.[10]

In equilibrium, the regional blend price of farm milk must exhaust the value of its components. Due to the component price wedges, the value of component k is itself a weighted average of its prices across products, namely $\frac{v_i^k \sum_{n\geq 1} \delta_i^{nk} Z_i^{nk}}{\sum_{n\geq 1} Z_i^{nk}}$, yielding the following regional farm milk blend price:

$$m_i = \sum_{k\geq 1} \zeta^k v_i^k \left(\frac{\sum_{n\geq 1} \delta_i^{nk} Z_i^{nk}}{\sum_{n\geq 1} Z_i^{nk}} \right) \,.$$

Using equation (2), the blend price can also be expressed as:

$$m_i = \frac{\sum_{k\geq 1} v_i^k \sum_{n\geq 1} \delta_i^{nk} Z_i^{nk}}{\sum_{j\geq 1} M_{ji}} \,. \tag{3}$$

Equation (3) makes apparent the analogy between the equilibrium price of milk in our model and the FMMO blend price, since the total classified value of components used in region i is divided by the total quantity of milk used in that region, and there is no value to milk beyond that embedded in its components.

Trade in farm milk between regions is subject to iceberg trade costs. Trade costs between origin region j and destination region i are denoted τ_{ji}, with $\tau_{ii} = 1$. Because farm milk is considered a homogeneous commodity, bilateral trade in farm milk is unidirectional, and milk prices between trading regions are related through trade costs. That is, denoting m_j the price of farm milk in region j, we have:

$$M_{ji} M_{ij} = 0 \quad \text{and} \quad \left\{ m_i = \tau_{ji} m_j \text{ whenever } M_{ji} > 0 \right\} \,.$$

The first equality states that if region j ships farm milk to region i, then i does not ship farm milk to j. The second condition states that under farm milk trade, the price of farm milk

[10] In the real world, components may be carried over from year to year, perhaps because product mixes and recipes cannot be adjusted easily in the short run to absorb an excess of component. The nonzero substitution elasticities across components in our one-shot model are meant to reflect long-run adaptation processes.

in the destination region exceeds that in the origin region by a factor equal to the bilateral trade cost. In terms of calibration, we handle observations of bidirectional trade in farm milk by computing net exports from one region to the other. We further reallocate milk shipments so as to eliminate loops (milk being transferred back to a source region through a sequence of bilateral trades).[11] One may rationalize instances of bidirectional trade in farm milk and the presence of loops by seasonality in local demand and supply conditions, a feature intentionally ignored in our analysis.

3.4 Milk production and derived demand for crops

Denoting by M_i the quantity of farm milk produced in region $i \geq 1$, equality between production and uses of farm milk implies that

$$M_i = \sum_{j \geq 1} \tau_{ij} M_{ij} \ .$$

We assume that milk is produced according to the following production function:

$$M_i = \min\left(F_i, \frac{N_i}{\nu_i}\right) \ ,$$

where F_i is a dairy feed crop aggregate, N_i is a composite of all non-feed inputs including livestock, and ν_i is the amount of non-feed inputs per unit of milk produced. Feed crops are indexed by $l = 1, \ldots, L$ and the dairy feed aggregate is defined as

$$F_i \equiv \left[\sum_{l \geq 1} \left(\omega_i^l\right)^{\frac{1}{\rho}} \left(F_i^l\right)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}} \ ,$$

where $\omega_i^l > 0$, $\sum_{l \geq 1} \omega_i^l = 1$, and $\rho \in (0,1) \cup (1,\infty)$ is the elasticity of substitution between feed crops used as dairy feed. Except for silage, a crop too bulky to be shipped out of its production region in any meaningful quantity, feed crop l may be traded between regions, with iceberg trade cost $\tau_{ji}^l \geq 1$ for a shipment from j to i. The quantity of feed crop l used by dairies in region i is also assumed to be an aggregate of physical quantities from different

[11]A loop is broken by reallocating the smallest trade flow while preserving regional milk production and use. There are four loops in the data; for each one, the flow being reallocated is very small relative to other flows in the loop.

origin regions, defined as

$$F_i^l \equiv \left[\sum_{j \geq 1} \left(\omega_{ji}^l \right)^{\frac{1}{\lambda^l}} \left(F_{ji}^l \right)^{\frac{\lambda^l - 1}{\lambda^l}} \right]^{\frac{\lambda^l}{\lambda^l - 1}} ,$$

where $\omega_{ji}^l > 0$, $\sum_{j \geq 1} \omega_{ji}^l = 1$, and $\lambda^l \in (0, 1) \cup (1, \infty)$ is the elasticity of substitution across origin regions for feed crop l. As we argue below, our market closure assumptions are such that the value of this substitution elasticity is immaterial to the equilibrium.

Denoting by w_j^l the price of crop l in region j, the milk-output-conditional demand, in region i, for crop l originating from region j is

$$F_{ji}^l = M_i \omega_i^l \omega_{ji}^l (W_i)^\rho \left(W_i^l \right)^{\lambda^l - \rho} \left(\tau_{ji}^l w_j^l \right)^{-\lambda^l} ,$$

where

$$W_i^l \equiv \left[\sum_{j \geq 1} \omega_{ji}^l \left(\tau_{ji}^l w_j^l \right)^{1 - \lambda^l} \right]^{\frac{1}{1 - \lambda^l}} \quad \text{and} \quad W_i \equiv \left[\sum_{l \geq 1} \omega_i^l \left(W_i^l \right)^{1 - \rho} \right]^{\frac{1}{1 - \rho}}$$

are price indices for dairy feed crop l and for the dairy feed crop aggregate in region i, respectively.

Perfect competition and the fixed-proportions milk production technology imply that the milk price in region i exhausts the production cost of farm milk, that is:

$$m_i = W_i + w v_i .$$

3.5 Crop trade and crop production

Feed crop l may be exported from region i to the ROW subject to iceberg trade cost $\tau_{i0}^l \geq 1$. We assume fixed world prices for feed crops, say w_0^l. Thus, if region i exports feed crop l internationally, the regional price of that crop is fixed at $w_i^l = \frac{w_0^l}{\tau_{i0}^l}$. Feed crops are not imported.

Feed crops may also be used in other animal sectors (beef cattle, poultry, etc.) or in the energy sector, and we assume fixed prices for crops in these sectors as well.[12] The quantities of feed crop l produced in region i that either reach the international market or are used outside of the U.S. dairy sector are aggregated together and denoted F_{i0}^l. Since grains and oilseeds are widely used in other livestock sectors, their prices in each region

[12]Due to the assumption of fixed prices, if a region exports crop l internationally and also uses that crop in non-dairy sectors, the price obtained in these sectors, net of any transportation cost, must be equal to w_0^l / τ_{i0}^l.

are fixed in the model. Given the relatively small share of these crops used by the dairy industry, this assumption seems reasonable. In contrast, a larger share of forage crops is used in the dairy industry and these crops are less likely to be exported internationally, so the regional prices of forage crops may be endogenous. Most hay is consumed locally, but a non-negligible share of it goes to sectors other than dairy, and in some cases it may also be exported internationally. Thus, we also treat the price of hay as exogenous.

The case of silage is less clear-cut. In many regions, silage is used mostly for dairy. Even where some silage is used in other sectors, dairy silage is often produced near dairies, non-dairy cattle that are fed silage may be located far from dairies, they may be fed silage of lower quality, and silage cannot be economically transported over long distances. That is, the market for dairy silage may be considered to be independent of other silage markets. We thus treat regional dairy silage prices as endogenous by defining silage as silage used exclusively for dairy and categorizing silage used in other sectors as part of a residual crop. (For an explanation of how we determine the regional share of silage used for dairy, see Supplemental Appendix B.4.)

In addition to dairy feed crops, farmers may produce an alternative crop representing an aggregate of all other crops competing for land (including non-dairy silage). This crop is indexed by $l = 0$, and we assume that its regional price, w_i^0, is fixed.

Denoting by Y_i^l the quantity of crop l produced in region i, total production is related to crop uses through the following equality:

$$Y_i^l = \sum_{j \geq 0} \tau_{ij}^l F_{ij}^l \ .$$

Crops are produced using constant-returns to scale technologies combining land and other inputs. Each region i has a fixed land base $L_i > 0$ and a continuum of parcels denoted ω that may be grown in at most one crop, with heterogeneous land productivity for crop l denoted $A_i^l(\omega)$ following a Fréchet distribution with shape parameter $\theta > 1$ and unconditional productivity $A_i^l > 0$.[13] As in Gouel (2025), the output of crop $l \geq 0$ from

[13]Specifically, the joint probability distribution for land productivity in region i is:

$$\Pr\left(A_i^l(\omega) \leq a^l, l = 0, \dots, L\right) = \exp\left[-\gamma \sum_{l=0}^{L} \left(\frac{a^l}{A_i^l}\right)^{-\theta}\right] ,$$

where the parameter γ is set so that $\mathbb{E}\left[A_i^l(\omega)\right] = A_i^l$ for all $l = 0, \dots, L$. See Costinot, Donaldson, and Smith (2016).

parcel ω is given by the following CES production function:

$$Y_i^l(\omega) = \left[\left(A_i^l(\omega) L_i^l(\omega) \right)^{\frac{\eta-1}{\eta}} + \left(\frac{N_i^l(\omega)}{\nu_i^l} \right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} ,$$

where $L_i^l(\omega)$ is the area of parcel ω grown in crop l and is equal to zero (if crop l is not chosen) or the entire parcel area $L_i(\omega)$ (if crop l is chosen), $N_i^l(\omega)$ is the quantity of inputs other than land on parcel ω, also chosen by farmers, and ν_i^l is a region- and crop-specific productivity parameter for these other inputs. The parameter $\eta \geq 0$ represents the elasticity of substitution between land and other inputs, with the limit case $\eta = 0$ denoting fixed proportions. We assume that there is limited substitution between land and other inputs in crop production, in the sense that $\eta < 1$. This limits the amount of intensification induced by increases in crop prices.

The CES nature of technology together with profit maximization imply that the crop price must be directly related to the input prices through the relationship

$$\left(w_i^l \right)^{1-\eta} = \left(\frac{r_i^l(\omega)}{A_i^l(\omega)} \right)^{1-\eta} + \left(w \nu_i^l \right)^{1-\eta} , \tag{4}$$

where $r_i^l(\omega)$ is the per area land rent for crop l. Equation (4) makes it apparent that the ratio $r_i^l \equiv \frac{r_i^l(\omega)}{A_i^l(\omega)} = \left[\left(w_i^l \right)^{1-\eta} - \left(w \nu_i^l \right)^{1-\eta} \right]^{\frac{1}{1-\eta}}$ is independent of the parcel. The total land rent from crop l on parcel ω is then

$$R_i^l(\omega) \equiv r_i^l(\omega) L_i^l(\omega) = \begin{cases} r_i^l A_i^l(\omega) L_i(\omega) & \text{if crop } l \text{ is chosen} \\ 0 & \text{otherwise} \end{cases} .$$

Given our distributional assumption regarding $A_i^l(\omega)$, the share of region i's cropland dedicated to crop l, which is also the probability that crop l be chosen, can then be expressed as

$$\pi_i^l = \frac{\left(r_i^l A_i^l \right)^\theta}{\sum_{l' \geq 0} \left(r_i^{l'} A_i^{l'} \right)^\theta} . \tag{5}$$

Using standard CES and Fréchet algebra, the regional supply of crop l can further be expressed as

$$Y_i^l = L_i A_i^l \left(\pi_i^l \right)^{1-\frac{1}{\theta}} \left(\frac{r_i^l}{w_i^l} \right)^\eta , \tag{6}$$

where the area share π_i^l, which is increasing in r_i^l and therefore in w_i^l, represents the extensive margin (area response), while the factor $\left(\frac{r_i^l}{w_i^l}\right)^{\eta}$, which is increasing in w_i^l, captures the intensive margin of crop supply. By the law of iterated expectations and Fréchet algebra, total land rents from growing crop l in region i are equal to

$$\begin{aligned} R_i^l = \quad & \mathbb{E}\left[R_i^l(\omega)\right] && = L_i \pi_i^l \mathbb{E}\left[r_i^l A_i^l(\omega) \middle| r_i^l A_i^l(\omega) \geq r_i^{l'} A_i^{l'}(\omega)\ \forall\, l' \geq 0\right] \\ = \quad & L_i r_i^l A_i^l \left(\pi_i^l\right)^{1-\frac{1}{\theta}} && = \left(w_i^l\right)^{\eta} \left(r_i^l\right)^{1-\eta} Y_i^l \,. \end{aligned} \tag{7}$$

4 Equilibrium in relative changes

We now derive the equilibrium in relative changes, which helps identify the most parsimonious set of data necessary to generate the counterfactual of interest. Added parsimony comes from the fact that although every parameter and variable considered previously has a clear empirical interpretation, not every one of them requires independent calibration to identify counterfactual effects (Donaldson, 2022).

4.1 Changes in prices and quantities

Because FMMO pricing rules have been operating for decades, share parameters calibrated using observed data reflect an equilibrium that includes component price distortions. Our policy counterfactual involves the removal of all such wedges in all FMMO regions. That is, $\delta_i^{nk} \neq 1$ for some (i, n, k) combinations in the baseline, whereas price wedges are all set equal to one in the counterfactual. The relative change in the price wedge, which is exogenous, is denoted $\hat{\delta}_i^{nk} \equiv \frac{1}{\delta_i^{nk}}$ and represents the ratio of the new to the old wedge.

The equilibrium in relative changes relates the change in the price wedges to the endogenous change in prices and quantities, also denoted with hats and representing the ratio of the new to the old values. The equilibrium is defined by a system of equations presented below, going from downstream dairy product markets to upstream crop markets.

The following equations relate to dairy product consumption in the U.S. and the ROW:

$$\hat{C}_{ij}^n = \left(\hat{P}_j\right)^{\kappa-\epsilon} \left(\hat{P}_j^n\right)^{\sigma^n-\kappa} \left(\hat{p}_i^n\right)^{-\sigma^n} \qquad i=0,\ldots,I, \quad j=1,\ldots,I, \quad n=1,\ldots,N \tag{8}$$

$$\hat{P}_j = \left[\sum_{n\geq 1} b_j^n \left(\hat{P}_j^n\right)^{1-\kappa}\right]^{\frac{1}{1-\kappa}} \qquad j=1,\ldots,I \tag{9}$$

$$\hat{P}_j^n = \left[\sum_{i\geq 0} b_{ij}^n \left(\hat{p}_i^n\right)^{1-\sigma^n}\right]^{\frac{1}{1-\sigma^n}} \qquad j=1,\ldots,I, \quad n=1,\ldots,N \tag{10}$$

$$\hat{C}_{i0}^n = \left(\hat{P}_0\right)^{\kappa_0-\epsilon_0} \left(\hat{P}_0^n\right)^{\sigma_0^n-\kappa_0} \left(\hat{p}_i^n\right)^{-\sigma_0^n} \qquad i=1,\ldots,I, \quad n=1,\ldots,N \tag{11}$$

$$\hat{P}_0 = \left[\sum_{n\geq 1} b_0^n \left(\hat{P}_0^n\right)^{1-\kappa_0}\right]^{\frac{1}{1-\kappa_0}} \tag{12}$$

$$\hat{P}_0^n = \left[\sum_{i\geq 1} b_{i0}^n \left(\hat{p}_i^n\right)^{1-\sigma_0^n}\right]^{\frac{1}{1-\sigma_0^n}} \qquad n=1,\ldots,N\ . \tag{13}$$

The following equations relate to dairy product manufacturing and the use of milk components:

$$\hat{Q}_i^n = \sum_{j\geq 0} a_{ij}^n \hat{C}_{ij}^n \qquad i=1,\ldots,I, \quad n=1,\ldots,N \tag{14}$$

$$\hat{Z}_i^{nk} = \hat{Q}_i^n \left(\hat{V}_i^n\right)^{\varsigma^n} \left(\hat{\delta}_i^{nk}\hat{v}_i^k\right)^{-\varsigma^n} \qquad i=1,\ldots,I, \quad n=1,\ldots,N, \quad k=1,\ldots,K \tag{15}$$

$$\hat{V}_i^n = \left[\sum_{k\geq 1} c_i^{nk} \left(\hat{\delta}_i^{nk}\hat{v}_i^k\right)^{1-\varsigma^n}\right]^{\frac{1}{1-\varsigma^n}} \qquad i=1,\ldots,I, \quad n=1,\ldots,N \tag{16}$$

$$\hat{p}_i^n = \psi_i^n \hat{V}_i^n + 1 - \psi_i^n \qquad i=1,\ldots,I, \quad n=1,\ldots,N\ . \tag{17}$$

The following equations relate to regional milk demand and milk prices:

$$\sum_{n\geq 1} \chi_i^{nk} \hat{Z}_i^{nk} = \sum_{j\geq 1} \mu_{ji} \hat{M}_{ji} \qquad i=1,\ldots,I \quad k=1,\ldots,K \tag{18}$$

$$\hat{m}_i \sum_{j\geq 1} \mu_{ji} \hat{M}_{ji} = \sum_{k\geq 1} \theta_i^k \hat{v}_i^k \sum_{n\geq 1} \theta_i^{nk} \hat{\delta}_i^{nk} \hat{Z}_i^{nk} \qquad i=1,\ldots,I \tag{19}$$

$$\left\{\hat{m}_j - \hat{m}_i \geq 0 \text{ and } \left(\hat{m}_j - \hat{m}_i\right)\hat{M}_{ji} = 0\right\} \text{ if } \mu_{ji} > 0 \qquad i=1,\ldots,I, \quad j=1,\ldots,I\ . \tag{20}$$

The following equations relate to regional production of milk and the use of feed crops:

$$\hat{M}_i = \sum_{j\geq 1} a_{ij}\hat{M}_{ij} \qquad i = 1, \ldots, I \tag{21}$$

$$\hat{F}^l_{ji} = \hat{M}_i \left(\hat{W}_i\right)^{\rho} \left(\hat{W}^l_i\right)^{\lambda^l-\rho} \left(\hat{w}^l_j\right)^{-\lambda^l} \qquad j = 1, \ldots, I, \quad i = 1, \ldots, I, \quad l = 1, \ldots, L \tag{22}$$

$$\hat{W}_i = \left[\sum_{l\geq 1} \xi^l_i \left(\hat{W}^l_i\right)^{1-\rho}\right]^{\frac{1}{1-\rho}} \qquad i = 1, \ldots, I \tag{23}$$

$$\hat{W}^l_i = \left[\sum_{j\geq 1} \xi^l_{ji} \left(\hat{w}^l_j\right)^{1-\lambda^l}\right]^{\frac{1}{1-\lambda^l}} \qquad i = 1, \ldots, I, \quad l = 1, \ldots, L \tag{24}$$

$$\hat{m}_i = \phi_i\hat{W}_i + 1 - \phi_i \qquad i = 1, \ldots, I\ . \tag{25}$$

The next set of equations relate to regional crop production:

$$\hat{Y}^l_i = \sum_{j\geq 0} \rho^l_{ij}\hat{F}^l_{ij} \qquad i = 1, \ldots, I, \quad l = 1, \ldots, L \tag{26}$$

$$\hat{Y}^l_i = \left(\frac{\hat{r}^l_i}{\hat{w}^l_i}\right)^{\eta} \frac{\left(\hat{r}^l_i\right)^{\theta-1}}{\left[\sum_{l'\geq 0} \pi^{l'}_i \left(\hat{r}^{l'}_i\right)^{\theta}\right]^{\frac{\theta-1}{\theta}}} \qquad i = 1, \ldots, I, \quad l = 0, \ldots, L \tag{27}$$

$$\left(\hat{w}^l_i\right)^{1-\eta} = \varphi^l_i \left(\hat{r}^l_i\right)^{1-\eta} + 1 - \varphi^l_i \qquad i = 1, \ldots, I, \quad l = 0, \ldots, L\ . \tag{28}$$

The final equations represent market closure conditions for commodities with exogenous prices, namely foreign dairy products and crops traded internationally and/or used in non-dairy sectors:

$$\hat{p}^n_0 = 1 \qquad n = 1, \ldots, N \tag{29}$$

$$\left\{\hat{w}^l_i - 1 \geq 0 \text{ and } \left(\hat{w}^l_i - 1\right)\hat{F}^l_{i0} = 0\right\} \text{ if } \rho^l_{i0} > 0 \qquad i = 1, \ldots, I, \quad l = 1, \ldots, L \tag{30}$$

$$\hat{w}^0_i = 1 \qquad i = 1, \ldots, I\ . \tag{31}$$

In addition to the shape parameters introduced in Section 3, Equations (8)–(31) feature a series of share parameters. For dairy products, $b^n_j \equiv \frac{P^n_j C^n_j}{P_j C_j}$ is the budget share of product n in total dairy consumption in region j; $b^n_{ij} \equiv \frac{\tau^n_{ij} p^n_i C^n_{ij}}{P^n_j C^n_j}$ is the share of product n from region i in total consumption of n in region j; and $a^n_{ij} \equiv \frac{\tau^n_{ij} p^n_i C^n_{ij}}{p^n_i Q^n_i} = \frac{\tau^n_{ij} C^n_{ij}}{Q^n_i}$ is the share of region i's production value of product n shipped to region j.

For milk components, $c^{nk}_i \equiv \frac{\delta^{nk}_i v^k_i Z^{nk}_i}{V^n_i Z^n_i}$ is the share of component k in the cost of milk components in product n in region i; $\chi_i^{nk} \equiv \frac{Z_i^{nk}}{\sum_{n'\geq 1} Z_i^{n'k}}$ is the share of product n in the use of component k in region i (in volume); $\theta_i^k \equiv \frac{\zeta^k v_i^k \left(\frac{\sum_{n\geq 1}\delta_i^{nk} Z_i^{nk}}{\sum_{n\geq 1} Z_i^{nk}}\right)}{m_i} = \frac{v_i^k \sum_{n\geq 1}\delta_i^{nk} Z_i^{nk}}{m_i \sum_{j\geq 1} M_{ji}}$ is the share of component k in total milk use value in region i; and $\theta_i^{nk} \equiv \frac{\delta_i^{nk} v_i^k Z_i^{nk}}{\sum_{n'\geq 1}\delta_i^{n'k} v_i^k Z_i^{n'k}} = \frac{\delta_i^{nk} Z_i^{nk}}{\sum_{n'\geq 1}\delta_i^{n'k} Z_i^{n'k}}$ is the share of product n in the value of component k in region i, which would be equal to χ_i^{nk} if not for the policy distortion.

For farm milk, $a_{ij} \equiv \frac{\tau_{ij} m_i M_{ij}}{m_i M_i} = \frac{\tau_{ij} M_{ij}}{M_i}$ is the share of region i's milk value shipped to region j and $\mu_{ji} \equiv \frac{M_{ji}}{\sum_{j'} M_{j'i}}$ is the share of milk used in region i originating from region j. Note that due to the trade costs in farm milk, $a_{ij}a_{ji} = 0$ and $\mu_{ij}\mu_{ji} = 0$. In addition, $\xi_i^l \equiv \frac{W_i^l F_i^l}{W_i F_i}$ is the share of crop l in total expenditure on dairy feed crops in region i, while $\xi_{ji}^l \equiv \frac{\tau_{ji}^l w_j^l F_{ji}^l}{W_i^l F_i^l}$ is the share of crop l from region j in total dairy expenditure on crop l in region i.

For crops, $\rho_{ij}^l \equiv \frac{\tau_{ij}^l w_i^l F_{ij}^l}{w_i^l Y_i^l} = \frac{\tau_{ij}^l F_{ij}^l}{Y_i^l}$ is the share of region i's production of crop l that is shipped to region j, with $j = 0$ denoting the international market or the feed market for animals other than dairy cattle.

Finally, cost shares at each stage of production reflect the relative importance of the factors represented explicitly in our model relative to the complementary inputs: $\varphi_i^l \equiv \frac{R_i^l}{w_i^l Y_i^l} = \left(\frac{r_i^l}{w_i^l}\right)^{1-\eta}$ is the total land rent relative to crop value for crop l in region i, that is, the regional land share of the crop l dollar; $\phi_i \equiv \frac{W_i}{m_i} = \frac{m_i - wv_i}{m_i}$ is the expenditure on dairy feed crops relative to the value of milk produced in region i, that is, the regional crop share of the milk dollar; and $\psi_i^n \equiv \frac{V_i^n}{p_i^n} = \frac{p_i^n - wv_i^n}{p_i^n}$ is the expenditure on milk components as a share of the price of dairy product n in region i, that is, the regional milk share of the dairy product n dollar.

4.2 Counterfactual welfare effects

Consider the representative consumer in region $j \geq 1$. If one ignores changes in land rents, the change in utility, calculated as the difference between utility in the counterfactual scenario, U_j', and utility in the baseline, U_j, represents the change in consumer surplus, the equivalent variation, and the compensating variation due to the change in dairy product prices:[14]

$$\Delta U_j \equiv U_j' - U_j = \frac{P_j C_j}{1-\epsilon}\left(1 - \hat{P}_j^{1-\epsilon}\right) .$$

[14]If one includes changes in factor incomes, here land rents, in the calculation, then the change in utility represents the change in social welfare.

Similarly, the effect on consumer surplus in the ROW for dairy products of U.S. origin is:

$$\Delta U_0 \equiv U_0' - U_0 = \frac{P_0 C_0}{1-\epsilon_0}\left(1 - \hat{P}_0^{1-\epsilon_0}\right) ,$$

where $P_0 C_0$ represents the value of exported dairy products.

We define total dairy product value as

$$PC \equiv \sum_{j\geq 0} P_j C_j .$$

Let $b_j \equiv \frac{P_j C_j}{PC}$ denote the share of total dairy product value that is consumed in region $j \geq 0$. One may then express the change in domestic consumer surplus relative to the value of domestic consumption as

$$\frac{\sum_{j\geq 1} \Delta U_j}{\sum_{j\geq 1} P_j C_j} = \frac{\sum_{j\geq 1} \frac{b_j}{1-\epsilon}\left(1 - \hat{P}_j^{1-\epsilon}\right)}{\sum_{j\geq 1} b_j} ,$$

and the total change in consumer surplus relative to total dairy product value as

$$\frac{\sum_{j\geq 0} \Delta U_j}{PC} = \frac{b_0}{1-\epsilon_0}\left(1 - \hat{P}_0^{1-\epsilon_0}\right) + \sum_{j\geq 1} \frac{b_j}{1-\epsilon}\left(1 - \hat{P}_j^{1-\epsilon}\right) .$$

Since we assume constant returns to scale in dairy, milk, and crop production, profit in our model is limited to rents accruing to landowners, the residual claimants of crop value. From Equation (7), the land rent in region $i \geq 1$ is equal to $\Pi_i \equiv \sum_{l\geq 0} R_i^l = \sum_{l\geq 0} \left(w_i^l\right)^\eta \left(r_i^l\right)^{1-\eta} Y_i^l$. The change in the regional land rent is:

$$\Delta \Pi_i \equiv \Pi_i' - \Pi_i = \sum_{l\geq 0} \varphi_i^l w_i^l Y_i^l \left[\left(\hat{w}_i^l\right)^\eta \left(\hat{r}_i^l\right)^{1-\eta} \hat{Y}_i^l - 1\right] ,$$

and the relative change in the regional land rent is then:

$$\frac{\Delta \Pi_i}{\Pi_i} = \sum_{l\geq 0} \frac{\varphi_i^l \rho_i^l}{\varphi_i} \left[\left(\hat{w}_i^l\right)^\eta \left(\hat{r}_i^l\right)^{1-\eta} \hat{Y}_i^l - 1\right] ,$$

where $\rho_i^l \equiv \frac{w_i^l Y_i^l}{\sum_{l'\geq 0} w_i^{l'} Y_i^{l'}}$ is the share of crop $l \geq 0$ in the value of crop production in region $i \geq 1$ and $\varphi_i \equiv \frac{\sum_{l\geq 0} R_i^l}{\sum_{l\geq 0} w_i^l Y_i^l} = \sum_{l\geq 0} \varphi_i^l \rho_i^l$ is the value of cropland relative to the total value of crop production in region i, that is, the regional land share of the crop dollar.

The total land rent impact, $\Delta\Pi \equiv \sum_{i\geq 1}\Delta\Pi_i$, can then be expressed relative to the aggregate land rent as

$$\frac{\Delta\Pi}{\sum_{i\geq 1}\Pi_i} = \frac{\sum_{i\geq 1}\rho_i\sum_{l\geq 0}\varphi_i^l\rho_i^l\left[\left(\hat{w}_i^l\right)^{\eta}\left(\hat{r}_i^l\right)^{1-\eta}\hat{Y}_i^l - 1\right]}{\sum_{i\geq 1}\varphi_i\rho_i},$$

where $\rho_i \equiv \frac{\sum_{l\geq 0} w_i^l Y_i^l}{\sum_{i'\geq 1}\sum_{l\geq 0} w_{i'}^l Y_{i'}^l}$ is the share of region i in the total value of crop production. For comparability with consumer effects and to compute social welfare effects, one may also express the change in land rent relative to total dairy product value:

$$\frac{\Delta\Pi}{PC} = \frac{a\psi\phi}{(1-\rho^0)(1-\xi_0)}\sum_{i\geq 1}\rho_i\sum_{l\geq 0}\varphi_i^l\rho_i^l\left[\left(\hat{w}_i^l\right)^{\eta}\left(\hat{r}_i^l\right)^{1-\eta}\hat{Y}_i^l - 1\right], \tag{32}$$

where $a \equiv \frac{\sum_{i\geq 1}\sum_{n\geq 1} p_i^n Q_i^n}{PC}$ is the share of domestic production in total dairy product value, $\psi \equiv \frac{\sum_{i\geq 1} m_i M_i}{\sum_{i\geq 1}\sum_{n\geq 1} p_i^n Q_i^n}$ is the milk share of domestic dairy product revenue, $\phi \equiv \frac{\sum_{i\geq 1} W_i F_i}{\sum_{i\geq 1} m_i M_i}$ is the overall feed crop share of milk revenue, $\rho^0 \equiv \frac{\sum_{i\geq 1} w_i^0 Y_i^0}{\sum_{l\geq 0}\sum_{i\geq 1} w_i^l Y_i^l}$ is the overall share of the non-feed crop in the value of total crop production, and $\xi_0 \equiv \frac{\sum_{j\geq 1}\sum_{l\geq 1}\tau_{j0}^l w_j^l F_{j0}^l}{\sum_{j\geq 1}\sum_{l\geq 1} w_j^l Y_j^l}$ is the share of total feed crop value used outside the dairy industry or exported.

5 Minimum calibration requirements

Conditional on model structure, the shape and share parameters in Equations (8)–(32) completely determine the price, quantity, and welfare effects of modifying the regional FMMO component price wedges. Many of the share parameters can be calculated from available data, yet mechanistic relationships exist between them, considerably reducing the amount of independent information necessary for calibration. In addition, some of our market closure assumptions imply that a few parameter values turn out to be immaterial to equilibrium. In what follows, we determine the minimum amount of information needed for our counterfactual analysis.

5.1 Dairy product expenditure and shipment shares

Because we do not model the ROW's consumption of non-U.S. dairy products, total dairy product value, PC, is equal to the value of domestic consumption plus the value of exports. PC must also be equal to the value of dairy products manufactured in the U.S. plus the value of imported dairy products. Therefore, we have:

$$\sum_{j\geq 0} P_j C_j = \sum_{i\geq 1}\sum_{n\geq 1} p_i^n Q_i^n + \sum_{n\geq 1}\sum_{j\geq 1} \tau_{0j}^n p_0^n C_{0j}^n \; .$$

Consequently, the expenditure shares by origin, b_{ij}^n, are related to the shares of production value by destination, a_{ij}^n, namely:

$$b_j b_j^n b_{ij}^n = a a_i a_i^n a_{ij}^n \qquad n \geq 1, i \geq 1, j \geq 0 \tag{33}$$

$$b_j b_j^n b_{0j}^n = (1-a) a_0^n a_{0j}^n \qquad n \geq 1, j \geq 1 \; , \tag{34}$$

where $a_i \equiv \frac{\sum_n p_i^n Q_i^n}{\sum_{i'\geq 1}\sum_n p_{i'}^n Q_{i'}^n}$ is the share of region i in the domestic value of dairy product manufacturing, $a_i^n \equiv \frac{p_i^n Q_i^n}{\sum_{n'} p_i^{n'} Q_i^{n'}}$ is the share of product n in the value of dairy product manufacturing in domestic region i, $a_0^n \equiv \frac{\sum_{j\geq 1} \tau_{0j}^n p_0^n C_{0j}^n}{\sum_{n'}\sum_{j\geq 1} \tau_{0j}^{n'} p_0^{n'} C_{0j}^{n'}}$ is the share of product n in the total value of dairy imports, and $a_{0j}^n \equiv \frac{\tau_{0j}^n p_0^n C_{0j}^n}{\sum_{j'\geq 1} \tau_{0j'}^n p_0^n C_{0j'}^n} = \frac{\tau_{0j}^n C_{0j}^n}{\sum_{j'\geq 1} \tau_{0j'}^n C_{0j'}^n}$ is the share of destination region j in the value of imports of dairy product n.

Summing Equations (33) and (34) over origin regions $i \geq 0$ yields:

$$b_j b_j^n = a \sum_{i\geq 1} a_i a_i^n a_{ij}^n + (1-a) a_0^n a_{0j}^n \qquad j \geq 0, n \geq 1 \tag{35}$$

with the convention that $a_{00}^n = 0$. Summing Equation (35) over dairy products $n \geq 1$ then yields:

$$b_j = a \sum_{i\geq 1} a_i \sum_{n\geq 1} a_i^n a_{ij}^n + (1-a) \sum_{n\geq 1} a_0^n a_{0j}^n \qquad j \geq 0 \; . \tag{36}$$

Therefore, if one knows a, a_i, a_i^n, and a_{ij}^n, one can deduce recursively the values of b_j, b_j^n, and b_{ij}^n.

5.2 Dairy component cost shares and dairy product shares in component value

The share of component k in the cost of dairy components for dairy product n in region i is given by c_i^{nk}, while the contribution of product n to the value of component k in that region is given by θ_i^{nk}. The relationship between these shares can be expressed as

$$a_i^n \psi_i^n c_i^{nk} = \theta_i \theta_i^k \theta_i^{nk} \qquad i \geq 1, n \geq 1, k \geq 1 \; , \tag{37}$$

where $\theta_i \equiv \frac{m_i \sum_{j\geq 1} M_{ji}}{\sum_{n\geq 1} p_i^n Q_i^n}$ is the value of milk used in region i relative to the value of dairy products produced in region i.

Summing Equation (37) over components k leads to

$$a_i^n \psi_i^n = \theta_i \sum_{k\geq 1} \theta_i^k \theta_i^{nk} \qquad i \geq 1, n \geq 1 . \tag{38}$$

Thus, if the parameters θ_i, θ_i^k, θ_i^{nk}, and a_i^n are known, (38) can be used to deduce ψ_i^n. One may then use (37) to deduce c_i^{nk}.

5.3 Farm milk trade shares

Regarding the movement of farm milk across U.S. regions, shipment shares by destination (a_{ij}) and availability shares by origin (μ_{ij}) are related through the relationship

$$\psi \mu_i a_{ij} = a_j \theta_j \mu_{ij} \qquad i, j \geq 1 , \tag{39}$$

where $\mu_i \equiv \frac{m_i M_i}{\sum_{i'\geq 1} m_{i'} M_{i'}}$ is region i's share of the total value of U.S. milk production. Summing Equation (39) over destination regions j leads to

$$\psi \mu_i = \sum_{j\geq 1} a_j \theta_j \mu_{ij} \qquad i \geq 1 . \tag{40}$$

Summing Equation (40) over origin regions i leads to

$$\psi = \sum_{j\geq 1} a_j \theta_j . \tag{41}$$

Thus, if one knows a_j, θ_j, and μ_{ij}, one may first use (41) to infer the value of ψ, then (40) to deduce the value of μ_i, and then (39) to deduce the value of a_{ij}.

5.4 Crop production and use shares

Equations (23), (24), and (26) may suggest that the definition of equilibrium requires knowledge of the parameters ξ_i^l, ξ_{ji}^l, and ρ_{ij}^l. In addition, deciphering the relative change in aggregate land rents as in Equation (32) requires knowledge of the crop production value shares ρ_i^l, ρ_i, and ρ^0 and the feed crop export share ξ_0. Here we argue that, due to our market closure assumptions in Equation (30) and the nature of our counterfactual, only the parameters ρ^0, ρ_i, ρ_i^l, ξ_0, and ξ_i^l are actually required, which greatly reduces the informational requirements.

Strictly speaking, Equation (30) allows the prices of non-silage feed crops to vary whenever non-dairy uses go to zero in the counterfactual. However, since our counterfactual involves a reduction in the farm milk price and therefore a reduction in milk production, feed crop uses in the dairy sector actually decrease, implying that prices of non-silage feed crops remain constant in all regions. Equation (24) then implies that $\hat{W}_i^l = 1$ for these crops regardless of the values of the procurement shares ξ_{ji}^l. Silage is not traded or used in other sectors, thus for this crop $\xi_{ii}^l = 1$ and Equation (24) implies that $\hat{W}_i^l = \hat{w}_i^l$. But then, Equation (22) with $j = i$ implies that $\hat{F}_{ii}^l = \hat{M}_i \left(\hat{W}_i\right)^{\rho} \left(\hat{w}_i^l\right)^{-\rho}$, so that λ^l disappears from the equilibrium conditions. Thus, a consequence of our model closure assumptions is that the Armington elasticities λ^l are irrelevant to the equilibrium, as are the values of the ξ_{ji}^l parameters for traded feed crops. Further, Equation (26) only serves to identify the change in feed crop use outside of the dairy sector, namely $\hat{F}_{i0}^l$, since this variable does not appear in any other equilibrium equation. Therefore, unless one is interested in tracking non-dairy feed use, knowledge of the ρ_{ji}^l parameters is superfluous.

The parameters ρ_i, ρ_i^l, and ξ_i^l can all be calculated from knowledge of regional crop production values ($w_i^l Y_i^l$ for $l \geq 0$) and/or regional values of feed crop use in dairy ($W_i^l F_i^l$), which we observe. The parameter ρ^0 can then be deduced as

$$\rho^0 = \sum_{i \geq 1} \rho_i \rho_i^0 \; . \tag{42}$$

From these data, one may also compute the share of total feed crop value used in the dairy sector in region $i \geq 1$, defined as

$$\xi_i \equiv \frac{W_i F_i}{\sum_{j \geq 1} \sum_{l \geq 1} w_j^l Y_j^l}$$

and, subsequently, the feed crop export share:

$$\xi_0 = 1 - \sum_{i \geq 1} \xi_i \; . \tag{43}$$

5.5 Crop share of milk revenue and land share of crop revenue

The regional feed crop share of milk revenue, ϕ_i, can be deduced from the overall feed crop share of milk revenue across regions, ϕ, the regional share of milk production value, μ_i, and the share of total feed crop value used in the dairy sector in region i, ξ_i, using the following relationship:

$$\phi_i = \frac{\phi \xi_i}{(1-\xi_0)\,\mu_i} \qquad i \geq 1\ , \tag{44}$$

where $1-\xi_0$ represents the share of the total value of feed crop production utilized by the domestic dairy industry. The parameter ϕ can be calculated from data on the value of feed crop use and the value of farm milk use across domestic regions.

Equations (5) and (6) imply that the regional share of land used for crop l, π_i^l, is related to the land share of crop revenue φ_i^l and the share of crop l in total crop value ρ_i^l through the equality

$$\pi_i^l = \frac{\varphi_i^l \rho_i^l}{\sum_{l' \geq 0} \varphi_i^{l'} \rho_i^{l'}} \qquad i \geq 1, l \geq 0\ .$$

One could consider calibrating the parameters φ_i^l using region-specific information on crop budgets and deducing the land shares π_i^l, yet data on cropland allocation is readily available and likely more reliable than crop budgets. Using the regional land share of the crop dollar $\varphi_i = \sum_{l \geq 0} \varphi_i^l \rho_i^l$, we have:

$$\varphi_i^l = \frac{\pi_i^l \varphi_i}{\rho_i^l} \qquad i \geq 1, l \geq 0\ . \tag{45}$$

Thus, to the extent that the parameters π_i^l, φ_i, and ρ_i^l can be calculated from available data, this expression determines the value of φ_i^l. Note that unlike φ_i^l, φ_i can be inferred directly from regional cropland value and regional crop production value without resorting to crop budget data.

5.6 Baseline component price distortions

The baseline price wedge factors δ_i^{nk} are deduced from comparing the parameters θ_i^{nk} and χ_i^{nk}, which represent regional shares of dairy product n in the value and the quantity of component k, respectively. We set the reference component prices for butter-powder in all regions, so that component prices are measured relative to the component price for use in butter-powder. Denoting $n = 4$ the index for butter-powder products, we thus have

$$\delta_i^{nk} = \frac{\theta_i^{nk} / \chi_i^{nk}}{\theta_i^{4k} / \chi_i^{4k}} \qquad i \geq 1, n \geq 1, k \geq 1\ . \tag{46}$$

6 Calibration information

There are $I = 12$ domestic regions corresponding to the 11 FMMO regions and a residual unregulated region. The regions in our model are composed of U.S. states that approximate the official boundaries of FMMO marketing areas, which rely on state boundaries but also county and in some cases township or city boundaries. Supplemental Appendix A provides the list of states included in each FMMO region as well as maps of the actual FMMO regions and the state-based delineations. Aggregation at the state level is necessary due to data limitations, notably regarding the Commodity Flow Survey of the U.S. Census Bureau, which is only available publicly at the state level. Nonetheless, we believe that our delineation captures most of the economically relevant differences in milk pricing across space. For example, several counties in Northern Idaho are included in the boundaries of the Pacific Northwest marketing order, yet the majority of Idaho's milk and crop production is located in the portion of the state which is not part of that marketing area. Most of the milk produced in Idaho being unregulated, it seems appropriate to include Idaho as a whole in the Unregulated region. In contrast, Maine is not included in any defined marketing area, but the vast majority of milk produced in Maine is regulated by the Northeast order. We thus include Maine in the Northeast region of our model to reflect this natural association.

We consider $N = 4$ dairy product categories corresponding to the four classes of milk specified in FMMO regulations, namely beverages, softs, cheese, and butter-powder products. Given that we model demand for dairy products at wholesale and that our policy counterfactuals involve changes in pricing rules for milk components across classes, we believe this categorization to be appropriate. Similarly, we consider the $K = 3$ components specified by FMMOs, namely butterfat, protein, and other solids. The $L = 4$ feed crops considered in the land allocation model—in addition to the residual crop—are grains, oilseeds, hay, and silage. Among those, only silage is assumed to be non-tradable across regions or internationally.

This section focuses on the calibration of the shape and elasticity parameters of our model, while Supplemental Appendix B describes the procedures used to compute the baseline share parameters. For those, most calibration data pertain to the year 2017.

6.1 Elasticities of demand for dairy products (ϵ, κ)

Two shape parameters govern the elasticities of dairy product demand: ϵ, the price elasticity of demand for the dairy product aggregate, and κ, the elasticity of substitution across dairy products. Specifically, the elasticity of demand for dairy product n in region j is:

$$\frac{\partial \ln C_j^n}{\partial \ln P_j^n} = (\kappa - \epsilon)\, b_j^n - \kappa \ . \tag{47}$$

Equation (47) implies that the absolute elasticity is bounded between ϵ (if $b_j^n \to 1$) and κ (if $b_j^n \to 0$). We would expect that $\kappa > \epsilon$ so that a product with a larger budget share has less elastic demand. Additionally, it makes sense for demand for dairy as a whole to be less elastic than demand for specific dairy products, and for products to be net substitutes, which happens whenever $\kappa > \epsilon$.

Gouel and Laborde (2021) refer to demand elasticities from a meta-analysis by Andreyeva, Long, and Brownell (2010) which includes cheese, milk, and other dairy products as explicit food categories. The mean demand elasticity for dairy products as a group was 0.65 in absolute value, with 95% of the observations between 0.46 and 0.84. However, the mean value of 0.65 was higher than the elasticities reported for milk and cheese, contrary to the expectation that the dairy aggregate should be less elastic than individual product categories. For beverage milk, the mean absolute elasticity was 0.59 and the 95% range was 0.40 to 0.79. Cheese was found to be slightly more inelastic, with a mean absolute elasticity of 0.44 and a 95% range of 0.25 to 0.63.

Okrent and Alston (2011) also survey the food demand literature to determine the range of elasticity estimates for food categories. In research that does not differentiate between food at home and food away from home, they find an average elasticity of demand for dairy products of -0.10, with a range from -0.04 to -0.19, suggesting much more inelastic demand than discussed in Andreyeva, Long, and Brownell (2010). Additionally, Okrent and Alston report mean demand elasticities of -0.42 for cheese, -0.30 for fluid milk, and -0.32 for ice cream.

Chouinard et al. (2010) estimate demand elasticities for a wider range of dairy products, including beverage milk products differentiated by fat content. The own-price elasticity estimates for reduced fat, skim, and whole milk lie between -0.63 and -0.74, while demand for low-fat milk is found to be much more elastic at -2.05. Since we are interested in targeting the elasticity of demand for beverage milk as a product category, we may want to target a more inelastic value. Additionally, Chouinard et al. (2010) provide own-price elasticity estimates for cream and other soft products (between -0.41 and -0.91), for cheese products (between -0.40 and -0.73), and for butter (-0.30).

These studies provide a target range for elasticities of demand for the four dairy product categories used in our model. Choosing values of $\epsilon = 0.2$ and $\kappa = 0.5$ produces elasticities of demand for each product category across regions that are within the target ranges. The resulting demand elasticities are reported in Appendix Table C.1.

6.2 Armington elasticity (σ^n)

Armington-style models often feature two nested levels of aggregation: one between domestic goods and overall imports, and another one across imports of different origins. This structure entails two elasticities of substitution, the first reflecting substitution between domestic and imported products and the second reflecting substitution across imports from different origins. In our model, the parameter σ^n is the elasticity of substitution across all possible origins of product n, i.e., the various domestic regions and the ROW. Studies that estimate trade elasticities may focus on either the domestic-import elasticity of substitution or the elasticity of substitution across origins of imports, and the appropriate σ^n may lie between these values.

Several widely-cited studies use a time-series approach to estimate trade elasticities and tend to find relatively inelastic values. Reinert and Roland-Holst (1992) estimate domestic-import elasticities of substitution across a wide range of sectors. For dairy product categories, they estimate elasticities of substitution of 0.67 for fluid milk, 1.00 for butter, and 1.99 for cheese. Gallaway, McDaniel, and Rivera (2003) utilize a similar approach but separately estimate short-run and long-run domestic-import substitution elasticities. They find elasticities of substitution of 1.00 for cheese in the short run and 1.35 in the long run and find identical estimates of 1.70 for butter in both the short and long run. For condensed milk and ice cream the authors can only estimate short-run elasticities, finding 0.59 for condensed milk and 0.50 for ice cream; they do not find a statistically significant estimate for fluid milk.

The time-series approach used in these studies has been criticized for producing substitution elasticities that are biased downward due to measurement error and simultaneity (Hillberry and Hummels, 2013; Hertel et al., 2007). Hertel et al. (2007) describe the assumption used in the Global Trade Analysis Project model, which uses a value for the import-origin substitution elasticity that is twice as large as the domestic-import elasticity. Additionally, Hertel et al. estimate the import-origin elasticity of substitution across a range of sectors using cross-sectional variation in trade costs across pairs of importers and exporters. For dairy products as an aggregate category, they estimate a mean elasticity of 7.3 with a standard deviation of 0.8.

Broda and Weinstein (2006) utilize a technique developed by Feenstra (1994) to estimate a wide range of import-origin elasticities for products at a highly disaggregated level. For soft products, elasticity estimates range from 1.81 to 7.76 with a median value of 4.03 and an average of 4.31. Substitution elasticities for cheeses and related products range from 1.55 to 12.32 with a median value of 6.34 and an average of 5.56. The estimated substitution elasticity for butter is 4.13, with dry and concentrated milk products elasticities ranging from 1.55 to 10.5 with a median of 3.6 and an average of 4.82. For milk and cream as an aggregate category, the elasticity estimate is 2.7. More generally, Broda and Weinstein find that estimated substitution elasticities are lower for more aggregate categories, and larger for products that could be considered homogeneous commodities rather than differentiated products.

While these studies provide a range of substitution elasticities applicable in an international trade context, far fewer studies consider trade elasticities applicable for regional analysis. In many cases regional trade models utilize trade elasticities from the international trade literature, with acknowledgement that such elasticities could be lower bounds for regional trade elasticities (Giesecke and Madden, 2013). To the extent that inter-regional trade faces fewer barriers than international trade, and transportation costs are often a smaller share of total costs for products traded regionally, the degree of substitution could be higher in a regional context as consumers are more price sensitive (Partridge and Rickman, 2010). However, Bilgic et al. (2002) estimate elasticities of substitution for regional trade that are comparable or even smaller than international trade elasticities. Bilgic et al. argue that regions may produce a wider set of products for domestic consumption than for the export market, resulting in more differentiation across regions and more inelastic substitution across origins.

With respect to dairy products traded within the U.S., it is likely that a wider variety of products are available to domestic consumers whereas only commodity products reach the export market. Product variety is more likely to have an impact for the soft products and cheese categories, while butter and dry milk products are commodity products even within the U.S. Additionally, since the four product categories used in our model are highly aggregated, the findings in Broda and Weinstein would suggest more inelastic substitution. Therefore, we use 2.5 as the elasticity of substitution for beverage products, 4.0 as the elasticity for soft products and cheeses, and 7.0 as the elasticity for butter and dry milk products. These elasticities reflect the ranges suggested by Broda and Weinstein (2006), while the higher elasticity for butter and dry milk products is closer to the elasticity suggested by Hertel et al. (2007).

6.3 Elasticities of foreign demand (ϵ_0, κ_0, σ_0^n)

In parallel to U.S. regional demand for dairy products of all origins, we parameterize the demand for U.S.-origin dairy products from the ROW. Since foreign consumers may substitute U.S. products with products originating from other parts of the world, foreign demand can be expected to be much more elastic than domestic demand.

Song and Kaiser (2016) evaluate the effectiveness of export promotion programs for dairy products and in doing so estimate the elasticty of import demand for U.S. dairy products across 10 importing regions to be equal to -1.06. Notably, this value is more inelastic than estimated foreign demand for other agricultural products. For instance, Reimer, Zheng, and Gehlhar (2012) estimate long-run elasticities of demand for U.S. crops of -1.64 for corn, -1.45 for soybeans, and -1.25 for wheat using data from 2001 through 2011. The U.S. share of the world dairy market is smaller than the U.S. share of the world corn or soybean markets, but dairy products are more heterogeneous than grains and oilseeds. Therefore, Reimer, Zheng, and Gehlhar may provide a reasonable range of elasticities to target.

With this in mind, we choose a more elastic value than that suggested by Song and Kaiser and set $\epsilon_0 = 1.3$. Choosing $\kappa_0 = 1.8$ implies elasticities of foreign demand for U.S. dairy products ranging from -1.71 for soft products to -1.56 for cheese, values that are in line with those suggested by Reimer, Zheng, and Gehlhar. These elasticities are reported in the last row of Appendix Table C.1. Note that there is no value for beverages as there are no exports of beverages to the ROW.

As discussed in the previous section, dairy products reaching the export market are likely to be less differentiated than those traded inter-regionally. Therefore, the values chosen for σ_0^n should be larger than the corresponding σ^n values. We thus choose an origin substitution elasticity of 8 for soft products and cheese and 10 for butter and dry milk powder products.

6.4 Elasticity of substitution across milk components in dairy production (ς^n)

The three milk components, namely butterfat, protein, and other solids, are used by dairy product manufacturers in various combinations. Depending on what product is being produced the combination may be close to fixed proportions. For example, most butter produced in the U.S. is 80% butterfat, but some higher-fat butter may also be produced.

It is common for researchers to assume fixed proportions when specifying production of dairy products. Chavas and Kim (2005) study hedonic pricing of American cheese, butter, and nonfat dry milk and assume that milk components are used in fixed proportions. However, since the authors study three specific products, fixed proportions may be a reasonable assumption. Coggins and Hammond (1994) specify a cheese yield formula based on the butterfat and protein content in milk but allow for a flexible functional form using a Box-Cox transformation. They test both a linear or perfect substitutes specification and a Cobb-Douglas specification, rejecting both functional forms. Coggins and Hammond do not specifically test a fixed-proportions specification, but these results suggest that substitution between milk components in cheese production is relatively inelastic. Gillmeister, Yonkers, and Dunn (1996) argue that milk component marginal product curves are inelastic, and that even if the production technology is not fixed-proportions, it is likely that the elasticities of substitution are small.

Given the variety of dairy product categories considered in our model, it is important to allow for different component substitution elasticities. For cheese and butter-powder products we set $\varsigma^n = 0.2$, allowing for a limited degree of substitution between milk components. While component substitutability in cheese production is limited due to the required protein and fat content in products, the butter-powder category includes products with widely different levels of required milk components, suggesting a high level of substitutability across components. Nonetheless, butter and powder products are often produced together in a given plant, since farm milk, which is the main input into the plant, is split into butterfat for use in butter and nonfat solids to be dried into nonfat dry milk. As a result, in practice substitution would be limited as plants would not specialize in either butter or powder products depending on relative prices, but rather produce a mix of both.

Beverage products range in fat content from skim milk to whole milk, with even higher fat beverage products commonly available. While the nonfat solids in beverage products are often at a similar level across various fat contents, the mix of products suggests that some substitution between components is possible. Hence, we set $\varsigma^n = 0.3$ for beverage products.

The soft products category includes the broadest set of dairy products, such as ice cream, yogurt, cream cheese, and infant formula, and therefore covers a broad set of product specifications. Manufacturers of specific products in this category may require milk components in fixed proportions due to plant restrictions, but across the product category milk components may be substituted more readily. Therefore, we set $\varsigma^n = 0.8$.

6.5 Elasticities of substitution across feed crops (ρ, λ^l)

As explained in Section 5.4, the values of the elasticities of substitution across feed crop origins, λ^l, are irrelevant to the equilibrium concept.

The elasticity of substitution between feed crops in dairy cattle feed, ρ, determines the regional output-constant elasticity of demand for feed crops:

$$\frac{\partial \ln F_i^l}{\partial \ln W_i^l} = -\rho \left(1 - \xi_i^l\right). \tag{48}$$

For crops representing a large share of feed expenditure ($\xi_i^l \to 1$), the elasticity of demand will be close to zero, whereas for feed crops with a small share ($\xi_i^l \to 0$) that elasticity will be close to $-\rho$.

Gouel and Laborde (2021) note that the literature on estimation of feed demand is limited, and studies that focus on feed demand by the dairy industry specifically are even less common. Rude and Meilke (2000) estimate feed demand in the European Union and find own-price demand elasticities for coarse grains and protein feeds of -0.70 and -0.32. Beckman, Keeney, and Tyner (2011) estimate U.S. feed demands in the context of substitution with biofuel by-products, estimating feed demand from the beef industry and finding elasticities of demand for energy feeds of -0.12 and for protein feeds of -0.05. Buccola and Iizuka (1997) use a hedonic cost modeling approach to evaluate the marginal cost of milk component production for U.S. dairy farms, estimating an elasticity of substitution of 0.25 between forage and feed concentrates, with corresponding own-price demand elasticities of -0.11 for feed concentrates and -0.13 for forages. In a study of the Spanish dairy industry, Casasnovas-Oliva and Aldanondo-Ochoa (2014) estimate a short-run feed demand elasticity of -0.23 and a long-run elasticity of -0.51.

These studies may provide some guidance on the value of ρ, but the substitutability between feed crops is also an important determinant of the implied elasticity of farm milk supply (along with the heterogeneity parameter θ). Therefore, ρ should ideally be chosen to target both the elasticity of feed demand and the elasticity of milk supply, which is discussed in further detail in Section 6.7. Using $\rho = 0.2$ results in a range of feed demand elasticities that are in line with those suggested by Beckman, Keeney, and Tyner (2011) yet have lower magnitude than those in Casasnovas-Oliva and Aldanondo-Ochoa (2014). These elasticities are shown in Appendix Table C.2. Note that Gouel and Laborde (2021) set $\rho = 0.9$, leading to more elastic demand for feed crops. However, they consider demand for feed from all livestock sectors, so a greater degree of substitutability between feed crops is to be expected in their context. Given that Buccola and Iizuka (1997) focus on the dairy industry, their estimate of 0.25 for the elasticity of substitution between forage and feed concentrates is a better reference value for our model.

6.6 Land heterogeneity and substitutability parameters (θ, η)

The shape parameter of the Fréchet crop yield distribution, θ, determines crop acreage elasticities:

$$\frac{\partial \ln \pi_i^l}{\partial \ln w_i^l} = \frac{\theta(1 - \pi_i^l)}{\varphi_i^l} , \tag{49}$$

and, given Equation (6), it also determines the crop output elasticities together with the crop intensification parameter η:

$$\frac{\partial \ln Y_i^l}{\partial \ln w_i^l} = \frac{\eta(1 - \varphi_i^l) + (\theta - 1)(1 - \pi_i^l)}{\varphi_i^l} . \tag{50}$$

Equation (49) shows that the crop acreage elasticity is decreasing in the regional acreage, which is intuitive as crops occupying a large share of available land have less room for expansion. The φ_i^l parameter is the ratio of land rent to crop value and is bounded between zero and one, with the acreage elasticity decreasing with a higher land share of the crop dollar. This is also intuitive as land is supplied inelastically in the aggregate whereas the other input is assumed to be supplied perfectly elastically.

In addition, the structure of the model imposes that, ignoring responses at the intensive margin (that is, assuming $\eta = 0$), the ratio of the crop output to the crop acreage elasticities be equal to $\frac{\theta-1}{\theta}$, which given $\theta > 1$ takes a value between zero and one. Given that most applications consider a value of θ close to one, the crop output elasticities are, by construction, much smaller than their acreage counterpart, although this discrepancy may be mitigated through the intensive margin component of supply response.

Many studies focus on U.S. acreage elasticities for corn and soybeans. In the context of crop rotation practices, Hendricks, Smith, and Sumner (2014) estimate long-run acreage elasticities for corn and soybeans of 0.29 and 0.26, respectively. Miao, Khanna, and Huang (2016) estimate U.S. corn and soybean acreage under alternative climate conditions and find acreage elasticities of 0.45 for corn and 0.63 for soybeans. These studies provide a range to target for the elasticities of grains and oilseeds. Hendricks, Janzen, and Smith (2015) provide estimates of growing area elasticities ranging from 0.29 to 0.30. These elasticities pertain to the sum of maize, rice, soybeans, and wheat areas and arguably provide a lower bound on the acreage elasticities pertaining to grains or oilseeds taken separately.

We choose $\theta = 1.01$ as our baseline value. Gouel and Laborde (2021) set $\theta = 1.1$ in their analysis based on a spatial unit of analysis representing a one-degree of latitude/longitude grid cell. There are thousands such cells across the continental U.S., thus it seems reasonable to assume higher heterogeneity in yields in our model. This choice also limits the magnitude of the acreage response elasticity. We choose $\eta = 0.1$ to allow for a reasonably small substitution between land and other inputs in crop production. Indeed, several studies including Roberts and Schlenker (2013) and Hendricks, Janzen, and Smith (2015) point to negligible responses of crop yields to crop prices, suggesting that the magnitude of crop output elasticities is expected to mimic that of acreage elasticities.

The implied crop supply elasticities are shown in Table C.3. Our parameterization produces crop output supply elasticities for grains and oilseeds that are generally in line with the values for acreage elasticities in Miao, Khanna, and Huang (2016), though these elasticities vary across regions to a great extent due to the differences in acreage shares. For example, oilseed crops occupy a very small share of cropland in the Pacific Northwest and Unregulated regions (less than 1%), leading to relatively large calculated oilseed supply elasticities. As expected, acreage elasticities are much larger in magnitude than the output supply elasticities, and they exceed the values in both Hendricks, Smith, and Sumner (2014) and Miao, Khanna, and Huang (2016). This clearly is a limitation of the Fréchet specification, as the acreage elasticity is bounded from below by $\frac{1-\pi_i^l}{\varphi_i^l}$, a ratio that often already exceeds the target values and over which the analyst has little control since the share parameters π_i^l and φ_i^l are both determined by observed data (see Section 5.5).

6.7 Milk supply elasticity

Our equilibrium model does not yield a closed-form expression for regional milk supply elasticities. Nonetheless, one may compute numerical values by using the supply-side of the model consisting of Equations (22)–(28) and (30)–(31) and treating the relative change in regional milk prices, $\hat{m}_i$, as exogenous. We thus assume simultaneous and equiproportional changes in milk prices across regions and solve for the regional changes in farm milk supply, $\hat{M}_i$. The implied regional milk supply elasticity is then given by:

$$\frac{\%\Delta M_i}{\%\Delta m_i} = \frac{\frac{\Delta M_i}{M_i}}{\frac{\Delta m_i}{m_i}} = \frac{\hat{M}_i - 1}{\hat{m}_i - 1} .$$

The shape parameters directly affecting regional milk supply are the land heterogeneity parameter θ, the crop intensification parameter η, and the substitution elasticity across feed crops, ρ.

Milk supply estimation has a long history, albeit with less focus in the recent literature. Since we are interested in simulating the long-term response to removal of FMMO pricing rules, we focus on long-run elasticities of milk supply. Chavas and Klemme (1986) develop a dynamic model of milk production based on herd composition, estimating a range of own-price elasticities for milk production over several time horizons. Their estimates of the long-run milk supply elasticity range from 2.46 at a 10-year horizon to 6.69 over a 30-year horizon. As an extension to this study, Chavas, Kraus, and Jesse (1990) consider regional milk production and herd sizes. While the regions used by Chavas, Kraus, and Jesse do not directly correspond to the marketing order regions used in this study, and milk production dynamics have changed over time in some regions, the regional elasticity estimates provide some insight into differences in supply elasticities across regions. Their overall estimate of the U.S. milk supply elasticity ranges from 1.53 at 10 years to 4.79 at 29 years. Regional milk supply elasticities at the 10-year horizon range from 0.35 in the South Atlantic to 3.65 in the Pacific region. Bozic, Kanter, and Gould (2012) update the Chavas and Klemme study with data from 2006–2010 and bootstrapped confidence intervals, estimating an aggregate U.S. milk supply elasticity at a 10-year horizon of 0.89 with a range from 0.68 to 1.14 and at a 25-year horizon of 2.33 with a range of 1.73 to 3.08.

Choosing values for ρ and θ that jointly meet the target elasticity ranges for the elasticity of feed demand, elasticity of crop supply, and elasticity of milk supply presents a challenge.

Table 1: Regional milk supply elasticities

Region	Elasticity	Region	Elasticity
Northeast	2.79	Mideast	2.18
Appalachian	1.07	California	3.38
Florida	4.20	Pacific Northwest	3.48
Southeast	1.97	Southwest	20.87
Upper Midwest	2.39	Arizona	5.59
Central	3.26	Unregulated	10.30
Total	5.20		

Source: Authors' numerical simulation of an equiproportional increase in regional milk prices.

Setting $\rho = 0.2$, $\theta = 1.01$, and $\eta = 0.1$ as we have done here produces elasticities of milk supply that appear quite reasonable on average, with significant regional variation. The aggregate milk supply elasticity is 5.2. The implied milk supply elasticities are shown in Table 1.

Given that land is the only productive factor supplied inelastically in our model, regional variation in implied milk supply elasticities can be explained by differences in the land intensity of milk production, itself a function of the feed crop share of the milk dollar, ϕ_i, the silage share of dairy feed expenditure, ξ_i^{silage} (silage being the only feed crop with an endogenous price in the model), the land share of the crop dollar for silage, $\varphi_i^{\text{silage}}$, and the acreage share of silage, π_i^{silage}. For instance, the Southwest region, which has the largest milk supply elasticity, has the lowest feed crop share of the milk dollar, the lowest silage share of dairy feed expenditure, and the second lowest land share of the silage crop dollar. The lowest land share of the silage crop dollar is found in the Unregulated region, which also has one of the smallest silage acreage shares and ends up having the second-largest milk supply elasticity. In contrast, the Appalachian region, which has the lowest milk supply elasticity, has the largest feed crop share of the milk dollar and the largest silage share of dairy feed expenditure. Interestingly, the Southwest region is one of the fastest growing milk-producing regions, with multiple dairy product manufacturing plants added or planned in Texas. It is reassuring that our calculations show the largest milk supply elasticity for that region.

6.8 Demand for milk components by end use

The canonical model of price discrimination across end uses of milk presented in Section 2.2 is predicated upon the fact that demand for beverage milk is more inelastic than demand for manufacturing milk. Although our calibrating information does not directly force any particular pattern of derived demand elasticities across end uses of farm milk, one can check that the implied elasticities in our structural model are congruent with the stylized fact that derived demand for beverage milk at the regional level should be more inelastic than derived demand for other dairy products, particularly those that can be more easily shipped like cheese and butter-powder.

One complicating factor, besides the fact that we must consider multiple FMMOs, is that the derived demand by end use pertains to components rather than farm milk. Thus, we report the regional elasticity of derived demand for milk components in product n, Z_i^n, with respect to its own milk component price index, V_i^n, holding constant the component price indices for other dairy products in region i and those for all dairy products in other regions. To compute these elasticities, we use the demand side of our model as represented by Equations (8)–(14), (17), and (29), treating the changes in component price indices $\hat{V}_i^n$ as exogenous. We increase the price of milk components for one dairy product in one region at a time, holding all other milk component prices constant, and compute the implied elasticity as:

$$\frac{\%\Delta Z_i^n}{\%\Delta V_i^n} = \frac{\hat{Q}_i^n - 1}{\hat{V}_i^{\,n} - 1}\,.$$

The resulting elasticities are reported in Appendix Table C.4 and confirm that milk component demand for use in beverage products is generally much less elastic than that for use in other products, particularly butter-powder. This result arises because of the larger substitution elasticity across origins for butter-powder products and the fact that all regions ship these products to the international market, where prices are fixed. The one exception is the Appalachian region, where the inelastic derived demand for milk components in butter-powder products can be traced to a particularly low cost share of milk components relative to other inputs.

7 Results and discussion

To give an idea of the extent and the pattern of component price distortions caused by the FMMO pricing rules, Table 2 shows the price wedge factors for protein and other solids in the beverage and cheese product categories relative to the default butter-powder products. Unlike the price of the butterfat component, the prices of protein and other solids tend to be heavily distorted, typically so in these two product categories. Relative wedges can be substantial for both protein and other solids, with factors sometimes in excess of 2 or below 0.5. In addition, wedge factors are not uniform across jurisdictions. For example,

Table 2: Selected price wedge factors

Region	Protein		Other Solids	
	Beverages	Cheese	Beverages	Cheese
Northeast	1.71	2.68	1.71	0.37
Appalachian	1.81	1.15	1.81	1.15
Florida	2.24	1.22	2.24	1.22
Southeast	1.95	1.23	1.95	1.23
Upper Midwest	1.48	2.29	1.48	0.52
Central	1.50	2.16	1.50	0.57
Mideast	1.51	2.55	1.51	0.42
California	1.39	1.10	1.39	1.16
Pacific Northwest	1.47	2.14	1.47	0.57
Southwest	1.65	2.02	1.65	0.62
Arizona	1.57	1.09	1.57	1.09

Source: Authors' calculations using Equation (46). Wedges are relative to component use in butter-powder. Wedges for the butterfat component are extremely close to one for all product categories and all regions and are not shown. The Unregulated region has no component price wedges and is not shown.

the Appalachian, Florida, Southeast, California, and Arizona regions have higher protein price wedge factors in beverages than in cheese, but the opposite holds in other regions. Finally, price distortions for protein and other solids are identical for beverages, but not necessarily for cheese.

We now explore a counterfactual scenario whereby the price differentials in each FMMO region are simultaneously removed. From a modeling standpoint, we set the relative change in the price wedge for component k in product n in region i, $\hat{\delta}_i^{nk}$, equal to $1/\delta_i^{nk}$, so that component prices are equated across classes in the counterfactual.

7.1 Changes in farm milk prices, production, shipments, and use

Table 3 summarizes regional changes in the farm milk market. Removing the FMMO pricing rules reduces the price received by milk producers, which decreases the quantity of milk produced. Depending on the region, the farm milk price decreases by either 0.3% or 0.1%. Recall that relative changes in regional prices are linked through milk shipments. In the baseline, milk shipments are such that each region is linked to every other, directly or indirectly, implying that the market for farm milk is fully integrated spatially across the U.S. (Due to transportation costs, this should not be construed as implying that the milk price is equated across regions, however.) In the counterfactual, this overall spatial

Table 3: Change in farm milk indicators

Region	Milk production value		Milk price	Milk produced	Milk used	Share of production value shipped out		Share of use value shipped in	
	(%)	(%)	(%)	(%)	(%)	(% pt.)	(%)	(% pt.)	(%)
Northeast	-1.05	[15.25]	-0.27	-0.78	-1.49	0.66	[8.31]	–	–
Appalachian	-0.56	[2.34]	-0.27	-0.29	-0.95	–	–	-0.51	[22.21]
Florida	-1.45	[1.35]	-0.27	-1.18	-3.62	–	–	-2.40	[5.06]
Southeast	-0.81	[1.05]	-0.27	-0.54	-5.11	–	–	-1.85	[61.60]
Upper Midwest	-0.93	[18.65]	-0.27	-0.66	0.62	–	–	1.21	[4.65]
Central	-1.17	[9.56]	-0.27	-0.90	-0.91	0.01	[4.84]	–	–
Mideast	-0.87	[10.06]	-0.27	-0.60	-4.78	–	–	-4.36	[0.48]
California	-0.60	[17.61]	-0.14	-0.46	-0.05	–	–	0.41	[1.12]
Pacific Northwest	-0.61	[4.35]	-0.14	-0.48	-3.87	3.40	[0.13]	–	–
Southwest	-7.31	[9.66]	-0.27	-7.06	-4.89	-1.98	[15.25]	–	–
Arizona	-0.91	[2.24]	-0.14	-0.77	-2.80	–	–	-2.03	[2.70]
Unregulated	-1.60	[7.88]	-0.14	-1.47	2.41	-3.72	[5.45]	–	–
Total	-1.56	[100]	-0.24	-1.32	-1.27	0.08	[3.64]	0.08	[3.64]

Notes: For milk production value, regional shares of total value are indicated in square brackets. For changes in shipment shares, baseline shares are indicated in square brackets. The share of production value shipped out is reported for regions with next milk exports in the baseline. The share of use value shipped in is reported for regions with net milk imports in the baseline. The Mideast region is a net milk importer in the baseline but becomes a net milk exporter in the counterfactual.

connectivity breaks down as milk shipments from the Unregulated region towards its non-Western destination regions are eliminated, giving rise to two separate milk markets, one comprising the Western portion of the U.S. (California, Pacific Northwest, Unregulated, and Arizona) where the milk price decreases by 0.1%, and the other comprising the other regions where the milk price decreases by 0.3%.

Importantly, overall farm milk shipments increase by 0.08 percentage points in value, a very modest increase relative to a baseline share of 3.6%. Therefore, surprisingly perhaps, it is not possible to impute the observed inter-regional shipments of farm milk at baseline to the component price distortions created by FMMO pricing rules. Rather, such shipments reflect market fundamentals related to comparative advantage in production and usage of milk. That is, regions with a comparative advantage in production, due for instance to silage availability, will tend to be net exporters of farm milk, while regions with a comparative advantage in milk transformation, either due to technological advantage or consumer preferences for geographical origin, will tend to be net importers.

We use our model to further quantify the importance of comparative advantage across domestic regions by considering another counterfactual whereby the bilateral transportation costs of farm milk, as captured by the τ_{ij} parameters, all increase in proportion; we then search for the minimum increase that completely eliminates domestic trade in farm milk. The new counterfactual model is described in Supplemental Appendix E. We find that an increase in transportation cost by 74% or more would cause all farm milk shipments to disappear. This considerable increase suggests that heterogeneity in milk production costs and use values across domestic regions is large and unlikely to be easily erased by policy.

Regional milk production decreases in all regions, with reductions ranging from 0.3% in the Appalachian region to 7.1% in the Southwest, by far the most affected region in terms of milk output. This is expected as the Southwest has the largest milk supply elasticity (see Table 1). Overall, the value of milk production across the U.S. decreases by 1.6%. In volume, overall milk production decreases by 1.3%.[15] This simulated decline in milk production is broadly consistent with the results of Chavas, Cox, and Jesse (1998), who consider scenarios where the FMMO pricing rules and price support programs are removed. Chavas, Cox, and Jesse find that U.S. milk production would fall by 1.8% when both programs are removed, with milk production falling across all regions they consider except California. By comparison, Ippolito and Masson (1978) estimate that Federal Order regulations lead to a 1.3% increase in milk production. However, they estimate that the price received by milk producers increases by 3.7%, a value much different from the 0.1–0.3% changes in milk price found in our simulation. This is due to a much larger value of the milk supply elasticity in our model.[16]

Reductions in regional milk output translate into reductions in regional dairy silage production. These reductions, which are not reported here, are modest, typically less than 1%, except in the Southwest where silage production decreases by 6.0%. The use of other dairy feed crops also decreases markedly in the Southwest, by 7.3%.[17]

Milk utilization falls in all regions except the Upper Midwest and the Unregulated region, while utilization in California falls by a negligible amount. The regions experiencing the largest declines in milk use are the Southeast, the Southwest, and the Mideast, with decreases in the order of 5%.

[15] Strictly speaking, the minimum calibration requirements described in Section 5 do not allow us to decipher the change in the total quantity of milk produced or used domestically, because regional milk shares are defined by value, not by volume. However, the primary data used to construct milk value shares does include information on farm milk quantities. We used that information to aggregate the regional milk production and use effects, as well as the milk price effect, to the national level. The aggregate milk price effect was computed based on production rather than use shares.

[16] Interestingly, Ahn and Sumner (2009) use price effects similar to ours to simulate the degree to which small increases in milk prices from FMMOs reflect the small amount by which political welfare weights of dairy farmers exceed those of dairy product consumers.

[17] Due to our market closure assumptions and Equation (22), the reduction in the use of dairy feed crops other than silage in any region is uniform across crops and origin regions.

Table 4: Change in component prices and cost indices

Region	Component price			Component cost index			
	Butterfat (%)	Protein (%)	Other Solids (%)	Beverage (%)	Softs (%)	Cheese (%)	Butter-Powder (%)
Northeast	4.42	44.70	11.19	-17.80	5.10	1.59	11.58
Appalachian	5.56	47.47	47.48	-11.01	11.09	12.93	18.33
Florida	6.65	93.74	93.74	-7.97	15.36	27.52	22.49
Southeast	-2.13	72.60	72.61	-8.63	7.61	17.46	13.11
Upper Midwest	2.21	86.62	-29.46	-18.60	-0.54	0.01	3.23
Central	2.30	50.65	-3.43	-15.09	1.87	1.43	6.39
Mideast	2.11	48.58	4.19	-13.25	2.58	-0.01	7.84
California	-0.18	11.89	13.91	-11.46	-0.53	-0.31	4.48
Pacific Northwest	1.31	50.63	-5.13	-14.62	0.60	0.36	5.57
Southwest	2.58	52.54	0.16	-18.26	2.46	3.29	9.59
Arizona	1.20	14.78	14.79	-17.35	2.97	2.23	11.53
Unregulated	-0.71	0.84	0.78	0.10	-0.13	-0.21	-0.03

Notes: The component price v_i^k is defined with respect to use in butter-powder products. The component cost index is defined by Equation (16) and reflects the cost of the milk component mix used in each product category.

7.2 Changes in Component Prices and Costs

With classified pricing, components tend to be priced higher for use in products other than butter and powder (see Table 2). Upon removing price differentials, we would expect the component price to converge to a value that lies between that in butter-powder products and those in other products. Since component prices are measured relative to butter-powder products, we expect the component prices to increase.

The first set of results in Table 4 shows the percentage change in component prices across regions. All three component prices increase in most regions, consistent with new equilibrium prices that lie between the highest- and lowest-cost uses. The component prices most affected by the removal of FMMO pricing are those for protein and other solids, which is expected as these are the components for which initial price wedges are the most sizable (see Table 2). The price of other solids actually decreases in the Upper Midwest, Central, and Pacific Northwest regions. These regions are among those where wedges for cheese products happen to be lower than one at baseline, putting downward pressure on the equilibrium price once the wedges are removed.

In contrast, the protein price increases in every region, which is expected as the protein price wedge is larger than one for beverages, soft products and cheese in all FMMO regions. As expected, the Unregulated region, which has no component price differentials at baseline, experiences the smallest changes in milk component prices.

Dairy products are manufactured from milk components in variable proportions, thus Table 4 also displays the change in the component cost index, V_i^n, which combines the individual changes in the prices of butterfat, protein, and other solids to reflect the overall change in the cost of milk components when used in each product category. The first column shows that the cost of components used in beverage products falls by between 8.0 and 18.6% across FMMO regions.

Component costs generally increase across the other dairy product categories, with cost increases generally lower for soft products and cheese and higher for butter-powder products. The largest component cost increases for non-beverage products are found in Florida, Appalachia, and the Southeast. These are also the FMMO regions experiencing the most moderate decreases in the beverage component cost.

7.3 Changes in dairy product value and exports

Changes in regional dairy product prices follow changes in the regional component cost index for each category shown in Table 4, although the change in component costs is not fully passed through to the product price due to complementary processing inputs. Thus, the price of beverage products falls in all FMMO regions while softs, cheese, and butter-powder products generally become more expensive.

Table 5 shows changes in the quantities of each dairy product produced regionally, in total production value, and in the value of dairy products exports. Following the decline in component costs for beverage products, most regions see an increase in beverage product output. Florida, the Pacific Northwest, and the Unregulated region are the only regions to experience a decline in beverage production, but with larger increases in output elsewhere, more beverage products are being shipped to those regions. For example, the large increase in beverage production in the Southeast (+4.9%) coincides with more shipments of beverage products to Florida (+7.1%), the Pacific Northwest (+7.2%), and the Unregulated region (+8.4%).

In most regions, production of butter and powder products declines, consistent with the decline in overall milk production seen across all regions, the overall shift towards beverage product manufacturing, and the increase in the cost of components for butter-powder use. Production of soft products and cheese declines in many but not all regions, with the most pronounced reductions happening in the Southeast and Southwest for cheese and the Southeast and Florida for soft products.

To aggregate across dairy product categories and regions, we also report the change in the value of dairy products. This change ranges from a decline of 4.3% in the Southeast

Table 5: Change in dairy product quantity, value and export value

Region	Production quantity				Total production value		International export value	
	Beverage (%)	Softs (%)	Cheese (%)	Butter-Powder (%)	(%)	(%)	(%)	(%)
Northeast	1.20	-0.77	-0.25	-2.91	-0.48	[20.27]	-0.28	[9.22]
Appalachian	1.00	-5.17	-3.91	4.37	0.15	[4.03]	-3.27	[2.28]
Florida	-0.61	-8.23	-1.14	-10.29	-2.21	[2.33]	-6.07	[5.49]
Southeast	4.93	-8.15	-17.90	-30.95	-4.29	[1.23]	-18.33	[1.13]
Upper Midwest	3.76	1.05	0.46	6.35	1.30	[15.74]	4.80	[12.48]
Central	0.29	0.32	-0.53	-0.79	-0.23	[11.30]	1.41	[9.68]
Mideast	1.87	0.47	0.51	-23.64	-0.32	[13.04]	0.29	[5.26]
California	0.25	0.62	0.89	-1.58	0.19	[13.90]	1.46	[30.86]
Pacific Northwest	-0.20	0.12	-0.00	-10.55	-1.22	[4.07]	-7.12	[7.05]
Southwest	1.31	-0.13	-6.39	-9.97	-1.78	[6.70]	-9.08	[8.24]
Arizona	1.71	-3.64	-2.92	-5.19	-1.75	[1.64]	-4.95	[1.39]
Unregulated	-2.04	0.70	0.78	7.98	1.10	[5.75]	7.16	[6.92]
Total	–	–	–	–	-0.17	[100]	-0.27	[100]

Notes: Baseline regional shares of total dairy production and export values are indicated in square brackets.

to an increase of 1.3% in the Upper Midwest, the only region to experience an increase in output of all dairy products categories. Overall, the value of U.S. dairy products falls by about 0.2%, meaning that the increases in production value in some regions barely offset the declines in others.

Table 5 also shows that the value of dairy product exports declines by about 0.3% for the U.S. as a whole. Exports fall by a large amount for some regions, up to 18.3% in the Southeast, which however represents the smallest share of exports at baseline across all regions (1.1%). These declines are partially offset by increases in regions responsible for a larger share of exports. For instance, exports from the Upper Midwest increase by 4.8% and exports from California increase by 1.5%. Both regions are major exporters of dairy products in the baseline.

7.4 Welfare effects

Table 6 indicates that removing the FMMO pricing rules would increase total social welfare by $210 million, a mere 0.1% improvement relative to the total value of the dairy market, PC. Domestic consumer surplus would increase by $340 million, largely due to the overall decrease in the price of beverage milk,[18] while foreign consumer surplus would fall by $47 million due the overall increase in the prices of other dairy products. Domestic land rents would decrease by $83 million due to the reduction in farm milk prices. Domestic social welfare would increase by the difference between consumer surplus and land rent changes, namely $257 million. Chouinard et al. (2010) summarize social cost estimates of FMMOs from prior work ranging between $184 million and $1.285 billion in 2017 dollars. Our simulated $257 million increase in domestic welfare lies towards the lower end of that range.

As with previous results, regional impacts are important to consider, with some regions faring better than others. The Northeast, Central, and Southwest regions see the largest gains in welfare, with increases of about $59 million, $42 million, and $38 million, respectively. Only one region, California, experiences a loss in social welfare due to decreases in land rents exceeding the increase in consumer surplus, while the Unregulated region breaks even. The simulated increase in consumer surplus in these two regions is relatively small. In California, this is due to a combination of a relatively small decrease in the price of local beverage products (1.2% as opposed to 2–3% for beverages manufactured in many other regions[19]) combined with a particularly high baseline expenditure share on butter-

[18]The producer price of beverage milk decreases in all domestic regions except the Unregulated region.

[19]Most beverages consumed in California are sourced locally as the expenditure share on local beverages reaches 85.5%. The beverage price index decreases only by 1.3% in California.

Table 6: Changes in consumer surplus, land rents, and social welfare

Region	Consumer surplus		Land rents		Social welfare	
	(%)	($ mn)	(%)	($ mn)	(%)	($ mn)
Northeast	0.16	[74]	-1.58	[-15]	0.028	[59]
Appalachian	0.16	[19]	-0.11	[-2]	0.008	[17]
Florida	0.20	[15]	-0.47	[-1]	0.007	[14]
Southeast	0.40	[32]	-0.04	[-1]	0.015	[31]
Upper Midwest	0.09	[22]	-0.27	[-18]	0.002	[4]
Central	0.19	[51]	-0.04	[-9]	0.020	[42]
Mideast	0.16	[30]	-0.19	[-10]	0.010	[20]
California	0.01	[3]	-0.28	[-9]	-0.002	[-5]
Pacific Northwest	0.29	[22]	-0.10	[-2]	0.009	[20]
Southwest	0.31	[48]	-0.90	[-9]	0.018	[38]
Arizona	0.62	[19]	-0.39	[-1]	0.009	[18]
Unregulated	0.05	[4]	-0.22	[-4]	0.000	[1]
United States	0.17	[340]	-0.17	[-83]	0.123	[257]
Rest of the World	-0.89	[-47]	–	–	-0.022	[-47]
Total	0.14	[293]	-0.04	[-83]	0.100	[210]

Notes: Changes in regional consumer surplus (including for the U.S. as a whole and the ROW) are relative to the regional value of dairy market consumption. Changes in regional land rents are relative to the regional land rents. Changes in social welfare as well as changes for Total are relative to the total value of the dairy market, PC. Absolute changes are indicated in square brackets.

powder products (18.9%), the price of which rises by 1.8%. As for the Unregulated region, it experiences very small changes in local dairy product prices, leading to moderate overall consumer effects as locally manufactured products also dominate consumption.

Land rents fall across all domestic regions along with farm milk and silage prices, with losses ranging from $1 million in the Southeast, Florida, and Arizona to $18 million in the Upper Midwest. Relative to baseline land rents, the largest effects are found in the Northeast with a 1.6% loss, and in the Southwest with a 0.9% loss. The reasons for these relatively large effects differ between the two regions: the Southwest experiences the largest decrease in the price of dairy silage (6.6%), while the effect in the Northeast is due to an unusually large share of cropland dedicated to dairy silage (22.4% as opposed to less than 10%, and often less than 5%, in other regions).

7.5 Sensitivity analysis

This section provides counterfactual results for alternative values of the shape parameters. We focus on parameters for which we believe that the empirical evidence is the weakest, namely the foreign dairy demand elasticities (ϵ_0 and κ_0), the milk component substitution elasticities (ς^n), the dairy feed crop substitution elasticity (ρ), and the crop production elasticities (θ and η).

Appendix Table D.5 summarizes our findings. In terms of milk production value, the effect of FMMO removal varies between -2.05% and -1.29% for the U.S. as a whole. The parameters most critical to the change in milk value are the substitution elasticities across components in dairy production. A more elastic value translates into a flatter derived demand for components in dairy products, notably non-butter-powder products, which, for a given component supply curve, makes for a larger decrease in component (and therefore milk) prices upon FMMO removal since the baseline price lies higher on the component supply curve.[20] The decrease in total milk value is most sensitive to the value of $\varsigma^{\text{cheese}}$ as cheese represents the most significant share of component value in many FMMO regions. Larger decreases in milk value, which are driven by larger decreases in farm milk prices, translate into lower consumer prices and thus larger consumer surplus gains for U.S. consumers, and lower losses for the ROW.

Larger increases in domestic consumer surplus also arise from more inelastic dairy feed crop supplies, corresponding to lower values of η and θ. Indeed, more inelastic dairy feed crop supplies translate into lower reductions in milk supply upon FMMO removal, and thus lower reductions in the volume of manufactured dairy products. In the stylized framework of Figure 1, a more inelastic milk supply implies that for the same reduction in the price of fluid milk from P^f to P^m, production of manufactured products decreases by a lesser amount. More inelastic crop supplies imply larger declines in land rents, however, since a larger share of the decrease in milk price gets capitalized in land values.

Domestic welfare effects range from 0.08 to 0.20% relative to the total value of the dairy market. Foreign welfare effects remain stable at -0.02%.

8 Conclusion

We develop a spatial equilibrium model of the U.S. dairy supply chain to investigate the impacts of longstanding FMMO pricing rules on the geography of milk production and processing, inter-regional trade in milk and dairy products, and the availability of

[20] This argument can be illustrated using Figure 1 if one views the two demand curves as reflecting derived demands for a particular component. A more elastic demand D^f at the baseline quantity Q^f implies a higher blend price P^b and therefore a larger decrease down to P^m.

dairy products to U.S. and foreign consumers. Although our model is more detailed, in its geographical resolution and representation of the production process, than most previous works, our calibrating information comports with stylized representations of FMMO pricing: component price differentials raise the price of beverage milk, decrease that of other dairy products with more elastic demand, and as a result increase the farm milk blend price and attendant farm milk production. While the qualitative effects of FMMO pricing are well understood, our structural supply chain model affords a comprehensive quantitative treatment of it, including welfare effects and impacts on inter-regional trade.

We find that the impacts of removing the FMMO pricing rules on farm milk production would be small nationally. The Southwest, the region most affected in percentage terms, would experience a 7.1% decrease in milk production and a 4.9% decrease in milk use. U.S. milk value would fall by 1.6%. A notable effect of removing component price differentials is the split of a previously spatially integrated market into two separate U.S. markets, one roughly comprising the Western portion of the U.S. and the other its Central and Eastern portions. Downstream, changes in the value of dairy product manufacturing and exports can be sizable, but only at the regional level.

Our simulation shows that dairy product buyers in the U.S. would gain $340 million in consumer surplus if FMMO pricing rules were removed, while international buyers of U.S. dairy products would lose $47 million. Due to the decline in milk production and attendant decline in demand for dairy feed crops, farmland owners would lose $83 million. Net welfare would increase by $257 million for the U.S. as a whole, and would increase in all U.S. regions except California.

Would the geographic footprint of U.S. dairy production be much different in the absence of FMMO pricing rules? In aggregate, shipments of farm milk as a share of production would increase slightly. Regionally, milk shipments from the Unregulated region would decrease substantially (by 3.7 percentage points, from a baseline share of 5.5%), as would Arizona's import share of milk use (by 2.0 percentage points, from a baseline share of 2.7%). Florida's import share of milk use would be cut in half, from a baseline value of 5.1%. The total value of dairy production in the U.S. would decrease by only 0.2%, but some regions, like the Southeast and Florida, would experience larger declines (4.3% and 2.2%, respectively). In contrast, the Upper Midwest, the second-largest region in terms of dairy production value at baseline, would experience an increase of 1.3%. The largest dairy producing region, the Northeast, would see a decrease of 0.5%.

FMMOs provide benefits to dairy farmers not accounted for in the present study, such as testing milk samples, market information, and product promotion efforts. Notwithstanding these benefits, our research shows that classified pricing and revenue pooling distort dairy market outcomes across the milk supply chain, though impacts are small in the aggregate.

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Supplemental Appendix

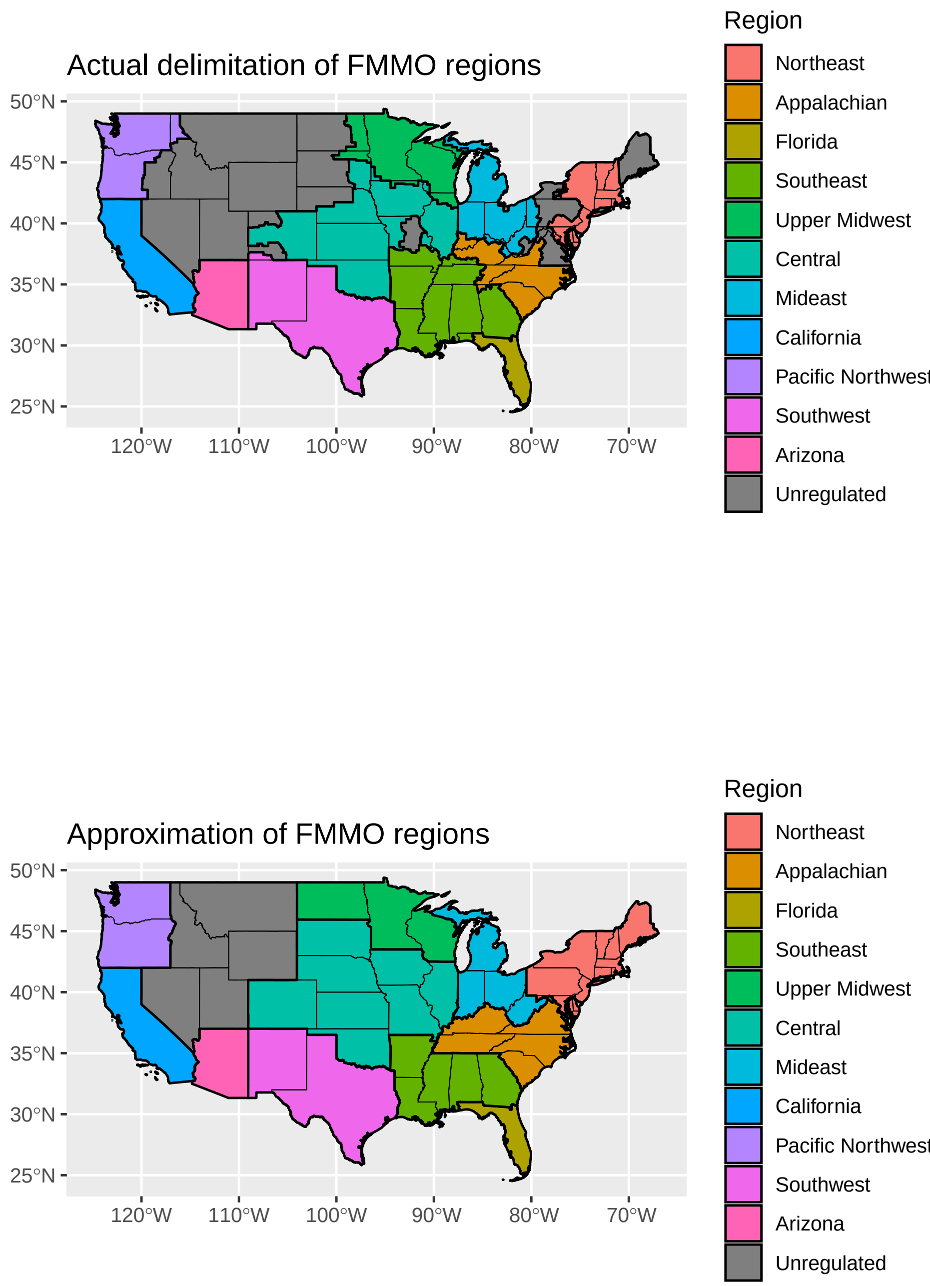
A State-based delineation of FMMO regions

Table A.1: States used to approximate FMMO regions

Region	Component States
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, Washington D.C.
Appalachian	Kentucky, North Carolina, South Carolina, Tennessee, Virginia
Florida	Florida
Southeast	Alabama, Arkansas, Georgia, Louisiana, Mississippi
Upper Midwest	Minnesota, North Dakota, Wisconsin
Central	Colorado, Illinois, Iowa, Kansas, Missouri, Nebraska, Oklahoma, South Dakota
Mideast	Indiana, Michigan, Ohio, West Virginia
California	California
Pacific Northwest	Oregon, Washington
Southwest	New Mexico, Texas
Arizona	Arizona
Unregulated	Idaho, Montana, Nevada, Utah, Wyoming

Source: Authors' determinations based on official FMMO marketing areas.

Figure A.1: FMMO regions and their approximations



B Calibration of share parameters

As explained in Section 5, one may classify the set of share parameters necessary for identification of the model in relative changes into two groups: parameters directly calibrated against data and parameters deduced from those using the relationships in Equations (33)–(46).

Table B.1 summarizes the entire set of share parameters, indicating whether they are directly calibrated against available data or whether their value is deducible from that of other parameters. The last column of the table indicates the source of the calibrating information. The rest of this appendix documents how the parameters listed in the upper panel of the table are recovered from the raw data. No share is directly observed; instead, shares are computed using information on value or quantity. Most calibration data pertain to the year 2017.

The parameters a, a_i, a_i^n, and a_{ij}^n are calculated using data from the U.S. Census Bureau, which provides information to recover inter-regional and international bilateral trade flows (in value) for each of the four dairy products considered in the model, including trade from each region to itself—which enables one to compute the value of regional production of each dairy product. See Section B.1 for details.

The parameter μ_{ij} is calculated from information on inter-regional farm milk shipments (in quantity) from USDA/AMS, including shipments from each region to itself. The parameters θ_i, θ_i^k, and θ_i^{nk} are calculated from information on the value of milk component use by class and by region, also from USDA/AMS; the parameter θ_i also uses the information on the regional value of dairy products described above. The parameter χ_i^{nk} is constructed from information on the quantity of milk component used by class and by region. The Unregulated region is not part of the FMMO system, therefore a different procedure is used to recover parameter values for that region. See Sections B.2 and B.3 for details.

The parameters ρ_i, ρ_i^l, ξ_i, and ξ_i^l are derived from information on crop production (at the state level), crop use including exports, industrial uses, food use, and feed use (at national level), and state-level information on animal inventories for key animal species to infer feed crop use by the dairy industry. This information comes from USDA. See Section B.4 for details.

The parameter ϕ is calculated from the value of feed crops used in the domestic dairy industry and the total value of milk component use described above.

The parameter φ_i is computed from regional information on cropland rental rates, cropland acres, and the value of crop production, all from USDA/NASS. See Section B.5 for details.

Finally, the parameter π_i^l is calculated from information on the regional allocation of

Table B.1: Share parameters and calibration sources

Share	Index range	Definition	Source
a		share of domestic production in total dairy product revenue	observed: Census Bureau, USDA/NASS
a_i	$i \geq 1$	share of region i in value of domestic dairy production	observed: Census Bureau
a_i^n	$i \geq 1, n \geq 1$	share of product n in value of dairy production in region i	observed: Census Bureau
a_{ij}^n	$i \geq 0, j \geq 0, n \geq 1$	share of region i's production of n shipped to region j	observed: Census Bureau
μ_{ij}	$i \geq 1, j \geq 1$	share of milk used in region j shipped from region i	observed: USDA/AMS
θ_i	$i \geq 1$	overall cost share of milk in dairy products made in region i	observed: Census Bureau; USDA/AMS
θ_i^k	$i \geq 1, k \geq 1$	share of comp. k in total milk value in region i	observed: USDA/AMS
θ_i^{nk}	$i \geq 1, n \geq 1, k \geq 1$	share of product n in value of comp. k in region i	observed: USDA/AMS
χ_i^{nk}	$i \geq 1, n \geq 1, k \geq 1$	share of product n in volume of comp. k in region i	observed: USDA/AMS
ρ_i	$i \geq 1$	share of region i in value of domestic crop production	observed: USDA/NASS
ρ_i^l	$i \geq 1, l \geq 0$	share of crop l in region i's value of crop production	observed: USDA/NASS
ξ_i	$i \geq 1$	share of total feed crop value used in region i's dairy	observed: USDA/NASS and USDA/ERS
ξ_i^l	$i \geq 1, l \geq 1$	share of crop l in value of region i's use of dairy feed crops	observed: USDA/NASS and USDA/ERS
ϕ		feed crop share of milk revenue	observed: USDA/NASS and USDA/ERS
φ_i	$i \geq 1$	land share of crop revenue in region i	observed: USDA/NASS
π_i^l	$i \geq 1, l \geq 0$	share of crop l in region i's total cropland	observed: USDA/NASS
b_j	$j \geq 0$	exp. share of region j in total dairy consumption	deduced from (36)
b_j^n	$j \geq 0, n \geq 1$	exp. share of product n in region j's dairy consumption	deduced from (35)
b_{ij}^n	$i \geq 0, j \geq 0, n \geq 1$	exp. share of origin i in region j's consumption of product n	deduced from (33) and (34)
ψ_i^n	$i \geq 1$	cost share of milk comp. for product n in region i	deduced from (38)
c_i^{nk}	$i \geq 1, n \geq 1, k \geq 1$	cost share of k (out of milk comp.) for product n in region i	deduced from (37)
ψ		milk share of (domestic) dairy product revenue	deduced from (41)
μ_i	$i \geq 1$	share of region i in value of domestic milk production	deduced from (40)
a_{ij}	$i \geq 1, j \geq 1$	share of region i's milk value shipped to region j	deduced from (39)
ρ^0		share of non-feed crop in value of domestic crop production	deduced from (42)
ξ_0		share of total feed crop value used outside of the dairy sector	deduced from (43)
ϕ_i	$i \geq 1$	feed crop share of milk revenue in region i	deduced from (44)
φ_i^l	$i \geq 1, l \geq 1$	land share of crop revenue for crop l in region i	deduced from (45)
δ_i^{nk}	$i \geq 1, n \geq 1, k \geq 1$	comp. price wedge relative to butter-powder product use	deduced from (46)

Note: Share parameters are those appearing in Equations (8)–(32) as well as ancillary share parameters defined in Section 5.

cropland acres from USDA/NASS.

B.1 Dairy product trade flows

Dairy product bilateral trade flows between domestic regions are calculated using data from the Commodity Flow Survey (CFS) of the U.S. Census Bureau. The CFS reports bilateral dairy product trade flows between states, but some observations are suppressed due to a lack of reliable data or a risk of revealing individual operations. The observed trade flows are preserved where available and interpolation is used to fill in the suppressed values. The procedure for interpolating inter-regional trade flows is adapted from Gabela (2020) and relies on available data on state-level values of production and consumption. The interpolation procedure assumes bilateral trade flows between regions follow a gravity-type model and is described in detail in Hanon (2023).

The CFS data do not identify shipments that are traded with the rest of the world. However, the Census Bureau reports state-level export data. Unfortunately, these data do not always correctly identify the state in which the shipment was produced. That is, if a shipment from one state is combined with another shipment from a different state prior to being exported, then the state-level export data will likely reflect the location where the two shipments were consolidated rather than the origins of the original shipments. The Census Bureau notes that this is especially common for unprocessed agricultural commodities since they may be exported by intermediaries and consolidation may occur prior to export. Exports of dairy products may face similar issues, especially for bulk commodity-type products that tend to be exported. However, it is common for large dairy manufacturing firms to be directly involved in exports, meaning consolidation prior to export is less likely and the state-level export data is more likely to accurately reflect the product origins.

The Census Bureau also reports state-level imports, which include a reported state of destination code, which we take as the state of final consumption.

B.2 Milk utilization in FMMO regions

Each FMMO reports the quantities of milk received and utilized by handlers who participate in revenue pooling. These data are compiled and published by USDA-AMS and provide the underlying observations to compute the share parameters related to farm milk shipments and utilization.

The data source for milk shipments between regions, M_{ij}, is the *Producer Milk Pooled by State of Origin* report for 2017. The report breaks down the total quantity of milk pooled in each FMMO by the state where the milk was originally produced. We aggregate these quantities to the FMMO level to generate a table of M_{ij} values. These values are then used to construct the μ_{ij} parameters.

Since our model assumes unidirectional milk trade flows, we calculate net flows in cases where bidirectional shipments between regions are observed. In addition, we reallocate milk shipments whenever some volume of milk is shipped back indirectly to a source region through a sequence of trades (loops, which are a generalization of bidirectional trade). Loops are broken by eliminating the smallest trade flow and reallocating shipments so that for each region, (i) the total volume of milk produced and (ii) the total volume of milk used remain the same as in the raw data.

AMS also publishes a *Utilization of Producer Milk* report for each product class, which includes the quantity of milk used in products from each class, the share of total milk pooled that was allocated to each class, and the component percentage of milk utilized in each class. These reports are published on a monthly basis, with an annual average calculated at the end of the year for each variable. Note that the component percentage of milk utilized in each class does not reflect a difference in milk composition across classes but rather how the components in farm milk are utilized across classes. For instance, in 2017 the average butterfat share of farm milk pooled in all Federal orders was 3.82 percent. However, since beverage milk products average around 2 percent butterfat, the butterfat share of milk used in Class I products was 2.04 percent. The additional butterfat from milk used to produce beverage products is often used to produce cream, which is a Class II product. As a result, the butterfat share of milk used in Class II products is typically higher than the farm milk butterfat share, averaging 7.42 percent in 2017.

Although milk components are allocated across uses in our model, the FMMOs must account for the total weight of all milk pooled. For example, suppose that 100 pounds of farm milk are used to produce skim milk and cream. If the farm milk is 3.8 percent butterfat, then 3.8 pounds of fat would be used to produce cream, a Class II product, and no fat would be used in skim milk, a Class I product. Since heavy cream is around 36 percent butterfat, 3.8 pounds of butterfat used in cream would amount to about 10.6 pounds of cream. Therefore, the FMMO data would show 89.4 pounds of Class I utilization (skim milk) at 0 percent butterfat and 10.6 pounds of Class II utilization (heavy cream) at 36 percent butterfat. While the FMMO data fully account for the 100 pounds of farm milk, our model is only concerned with the component allocation and uses these data to determine the pounds of fat (and other components) utilized in each class.

Ideally, we could use the component shares and the pounds of milk utilized in each class to calculate the quantity of component k used in product n, Z_i^{nk}. However, the FMMO data only reflect the utilization of components in milk that is regulated by the federal orders. In other words, the total quantity of milk pooled may understate the quantity of milk processed in each region. In addition, we cannot assume that milk not pooled is utilized in the same proportions as pooled milk, since any milk utilized in Class I products must be pooled; thus, any milk not pooled must be utilized in products from Classes II, III, or IV.

To impute the utilization of milk not pooled, we use two pieces of data from the monthly *Utilization of Producer Milk* reports from AMS: the utilization share for each class (the percentage of all milk pooled in a given month that was utilized in each class) and the quantity of milk pooled in each month. First, using the utilization shares, we calculate the annual average utilization share by class and the deviations between the monthly utilization shares and the annual average. Then, we divide the quantity of milk pooled by the number of days in the month to determine the average daily milk pooled. Since we are calculating deviations from average, this step ensures that we can compare January and February without the number of days impacting the comparison. We then multiply the average daily milk pooled by the utilization shares to determine the average daily milk utilized in each class, and again calculate the annual average and deviations from that average.

We assume that milk not pooled is used in products from a given class in a given month if the deviations from the average utilization share and the average daily milk utilized are negative for that month. For example, in the Central Federal Order about 40 percent of milk pooled was used for Class III products on average in 2017. However, in October, November, and December the utilization share fell to between 20 and 30 percent, suggesting that some portion of milk used in cheese production was not pooled in those months. We then take the sum of the deviations of average daily milk utilized across the months we identified as having milk not pooled in a given class. Since pooling Class I milk is mandatory, we only calculate these sums for Class II, Class III, and Class IV. Using the total deviations for Classes II, III, and IV, we calculate the share of the quantity of milk not pooled attributable to each class. In the Central Federal Order 72 percent of the quantity deviations were from Class III, so we assume that 72 percent of milk not pooled in the Central region was used in cheese manufacturing. Table B.2 reports the imputed utilization shares for each class and each region.

The imputed utilization shares for milk not pooled allow us to allocate the use of milk not pooled across the three non-beverage classes of utilization. Doing so requires knowing the quantity of milk not pooled in each region, which can be calculated as the difference between the total quantity of milk produced in each region (based on NASS milk production data) and the total quantity of milk pooled, either in the region or elsewhere. (This calculation assumes that milk not pooled is used within its region of production.) Using these imputed allocations, and the utilization shares for pooled milk published in the FMMO data, we can calculate the total quantity of component k used in product n, Z_i^{nk}.

Given the quantities of milk components used in each class, the value of these components is calculated using the *Final Class and Component Price* reports published by AMS.

Table B.2: Imputed utilization shares for milk not pooled (%)

Region	Softs	Cheese	Butter-Powder
Northeast	30	11	60
Appalachian	22	14	65
Florida	28	41	31
Southeast	6	62	32
Upper Midwest	11	82	6
Central	9	72	19
Mideast	30	53	17
California	0	100	0
Pacific Northwest	3	95	3
Southwest	3	83	14
Arizona	4	37	58

Source: Authors' calculations using data from USDA AMS reports, *Producer Milk Pooled by State of Origin* and *Utilization of Producer Milk*.

Notes: The California Milk Marketing Order enforced mandatory pooling for all Grade A milk (milk meeting the sanitary standards required for use in beverage products) and was still in effect in 2017. Any milk not pooled in California (which would be Grade B) was assumed to be used for cheese production.

These reports include each of the component prices across classes. We use the Class IV component prices as the baseline values for v_i^k, with the component prices for each other class equal to $\delta_i^{nk} v_i^k$. While Class I prices vary by region, with Class I differentials specified at the county level, component prices for Classes II, III, and IV are common across regions. This could suggest that δ_i^{nk} is equal across regions for Classes II, III, and IV. However, due to the presence of milk not pooled in each region, this is not the case. We use the Class IV component prices to value milk not pooled regardless of end use. Therefore, for a given FMMO region we add together the value of pooled milk components, valued at the component price for the product class in which they were utilized, and the value of milk components not pooled, valued at the baseline Class IV component prices. The combined value represents $\delta_i^{nk} v_i^k Z_i^{nk}$. This calculation implies that a region with a higher share of milk not pooled will have a δ_i^{nk} closer to one, the baseline value.

Calculating the value of components does involve some differences across marketing orders, which also result in some further variation in the δ_i^{nk} values. Most of the current FMMOs use component-based pricing across Classes II, III, and IV, where minimum component prices are set for each class and used to calculate the classified value of milk components. Class III is the only class in which separate prices are used for fat, protein, and other solids, while Classes II and IV use a fat price and a nonfat solids price. In each of these cases the classified value is easily calculated as the product of the component prices and the quantity of components used in each class.

Four FMMOs, the Appalachian, Florida, Southeast, and Arizona orders, use a skim-fat pricing method where a minimum price is set for fat and skim milk in each class. Additionally, all FMMOs use this method for Class I milk use. The value of fat used in each class is calculated in the same way as the component-priced orders, but the quantity of skim milk used is calculated from the difference between milk use and fat use. Using the skim milk price for each class, we compute the value of skim milk and then apportion this value between protein and other solids. Note that by using the whole quantity of skim milk in this calculation, the Federal orders that use a skim-fat pricing method implicitly value the water in milk. However, by attributing the skim milk value to protein and other solids, our model assigns no value to water. We believe this more accurately reflects the value of milk components, and ensures consistency between the skim-fat pricing orders and multiple component pricing orders. We assign the skim milk value to protein at a ratio of 3.1:9 and other solids at a ratio of 5.9:9. These ratios come from the FMMO regulations used to define the Class III skim milk price, so they represent the method that USDA/AMS uses to assign individual component values to skim milk.

B.3 Milk utilization in the Unregulated region

While the prior section describes how we determine the quantity and value of milk components utilized in each product category in the FMMO regions, Z_i^{nk} and $\delta_i^{nk} v_i^k Z_i^{nk}$, we also need to determine that information for milk components utilized in the Unregulated region. Unfortunately, the data published by the FMMOs does not include information on how unregulated milk is utilized, therefore it is difficult to assign the components in milk that is produced in the Unregulated region and has not been shipped to an FMMO region to product categories. (The Unregulated region does not receive milk shipments from other regions.)

State level milk production data published by USDA-NASS provides the total quantity of milk produced in the Unregulated region. Combined with USDA-AMS data on milk shipped out of the Unregulated region we can calculate the quantity of milk processed in the Unregulated region. The next step is to determine the total quantities of components utilized in processing in the Unregulated region. We can calculate the total quantity of butterfat utilized in the Unregulated region using USDA-NASS state-level butterfat share data, i.e., the pounds of butterfat in 100 pounds of milk. NASS does not publish nonfat solids share data, so we assume the nonfat solids share of milk produced in the Unregulated region can be approximated using the USDA-AMS average nonfat solids share across all FMMO regions. Multiplying the butterfat and nonfat solids shares by the quantity of milk utilized yields the total quantity of components utilized in the Unregulated region. In other words, we know $\sum_n Z_i^{nk}$, but cannot yet identify Z_i^{nk} separately.

We first approximate the value of components used in beverage milk products. We use fluid milk consumption per capita published by USDA-ERS and state-level population to compute beverage milk consumption by state and aggregate across states in the Unregulated region. As discussed previously, any Class I milk utilization distributed in an FMMO marketing area must be regulated under that FMMO. This applies even when the bottling plant is geographically located outside of the FMMO marketing area if a sufficiently large amount of beverage milk products from that plant are distributed in the marketing area. Therefore, since any beverage milk products produced in the Unregulated region and shipped to a different FMMO region would be regulated under that FMMO, beverage milk consumption in the Unregulated region is equivalent to the quantity of unregulated milk utilized in beverage products in that region.

Given the quantity of milk utilized in beverage milk in the Unregulated region, we assume the components used in beverage milk products can be approximated using the average quantity of components used in Class I products in the FMMO regions. We can then subtract the quantities of components used in beverage products from the total quantities of components used in the Unregulated region to determine the residual quantities of component used in manufactured products.

In order to determine how the residual components used in manufactured products are utilized across different product categories, we calculate the quantities of components in specific products manufactured in the Unregulated region. USDA-NASS publishes the *Dairy Products Annual Summary*, which reports production quantities for several major dairy products. Production is reported for the U.S. as a whole, three regions (Atlantic, Central, and West), and a selection of states for each product. Unfortunately, NASS groups states into an "Other States" category if a state has fewer than three plants manufacturing a given product or if the observation would identify a specific operation. However, we can use the known state observations to calculate the residual production in each region that is attributable to the "Other States" category and use this to deduce state-level production that is not reported.

For example, cheese production is reported for California, Idaho, New Mexico, and Oregon as individual states from the West region. These four states produced about 4.45 billion pounds of cheese in 2017, or about 85 percent of the 5.22 billion pounds produced in the West region. The remaining 773 million pounds of cheese produced in the West must be produced in the other West region states, and we use the share of milk production among the remaining states to assign cheese production values. Among the states without specifically-reported cheese production, 34 percent of milk production is in Washington, therefore we assume about 264 million pounds of cheese was produced in Washington. We use milk production as a weight in this calculation rather than milk utilization since we have state-level observations of milk production yet only regional observations for utilization.

Once we have apportioned the production of each dairy product across states, we use conversion factors published by USDA-ERS to determine the quantities of components in each product.[21] For example, according to the ERS conversion factors, cheddar cheese contains 33.31 percent butterfat and 29.67 percent nonfat solids. Therefore, for every 100 pounds of cheddar cheese produced in a given state we know about 33 pounds of butterfat and 30 pounds of nonfat solids were utilized to produce cheese. After applying these conversion factors to the state-level production of each dairy product, and assigning those products to the three manufacturing product categories used in our model (soft products, cheese and whey, and butter and powder products), we sum across dairy products to determine the total quantities of components utilized in products in each category.

Finally, we sum across the states in the Unregulated region to determine the total component quantities utilized in each product category. Since the NASS *Dairy Products Annual Summary* includes production quantities for only select dairy products, these totals do not account for all of the residual quantities of components used in manufactured products calculated previously. However, we can use these data to calculate the share of each component utilized in each product category and apply those shares to the residual components used in manufactured products. These shares are approximations for the Unregulated region of the Class II, III, and IV component utilization shares reported by AMS for each FMMO.

Multiplying these shares by the residual components used in manufactured products yields the quantities of components used in each product category, Z_i^{nk}, for the Unregulated region. Since component prices are not distorted across product categories in the Unregulated region, we use a single component price for each category, v_i^k, to determine the value of components used in each product category, $v_i^k Z_i^{nk}$. As with the FMMO regions, we use the Class IV component prices to represent the base-level component prices without distortion.

[21]The conversion factors used by ERS can be found in the documentation for their dairy data: https://www.ers.usda.gov/data-products/dairy-data/documentation/

B.4 Regional feed crop production and consumption

Regional crop production values are calculated using USDA-NASS data. The primary source for these data is the 2017 Census of Agriculture, but the Census does not include production values for hay and silage, so NASS Crop Production reports are used to complete the dataset.

In contrast, the value of feed crop consumption by the dairy sector is not readily available due to the wide range of possible crop uses. For example, corn may be used as dairy feed, used as feed in another livestock sector, or used in a separate industry entirely (such as the energy sector). Thus, we first determine the share of regional crop availability used as livestock feed and then further determine the share of feed crops used by the dairy sector.

Starting with the value of crop production in each state, we sum to the national level to determine the total value of U.S. crop production. Using data from the U.S. Census Bureau on the value of crop exports, we then subtract the value of U.S. exports of each commodity group (corn, other grains, soybeans, other oilseeds, and hay) from the total value of crop production to determine the value of domestic crop consumption.

We then use data published by USDA-ERS on domestic crop utilization to determine the share of each commodity group used as livestock feed. ERS reports uses of feed grains and oilseeds in the *Feed Grains Yearbook* and the *Oil Crops Yearbook*, including a breakdown of domestic use. Domestic uses of feed grains include food, alcohol, industrial, and seed, with feed calculated as the residual use case. Note that by using the "feed and residual" category to calculate the share of grain crops used for animal feed, we may overstate the actual quantity of grains used for feed. The *Feed Grains Yearbook* breaks down domestic use for corn, sorghum, barley, and oats. The data on sorghum, barley, and oats are combined to calculate a feed use share for the other grains commodity group. In addition, ERS reports supply and utilization of corn byproducts, including dried distillers' grains, corn gluten meal, and corn gluten feed, in their *U.S. Bioenergy Statistics* data. We assume these byproducts are also used as livestock feed, and therefore include them in the total quantity of corn used as feed.

In the *Oil Crops Yearbook*, oilseed domestic use is categorized into biofuel use, edible uses, crush, or "seed, feed, and residual." Similar to the feed grains use data, feed use and seed use are combined in a residual category, so using this category to calculate feed use may overstate the quantity of oilseeds used directly as feed. However, unlike feed grains, oilseeds are seldom directly fed to livestock. Instead, oilseed meals are the primary form in which oilseeds are used as livestock feed. The *Oil Crops Yearbook* data include the quantities of oil and meal produced from oilseeds used for crush, so we can include oilseed meals in the quantity used for animal feeds. For oilseed meals we assume that the quantity that is not exported is used as animal feed, while oilseed oils are not used as feed.

Table B.3: Share of domestic crop consumption used as livestock feed

Commodity	Share
Grains	
Corn	0.438
Other grains	0.453
Oilseeds	
Soybeans	0.785
Other oilseeds	0.685
Hay	1.000
Silage	1.000

Source: Authors' calculations based on USDA/ERS *Feed Grains Yearbook*, *Oil Crops Yearbook*, and *U.S. Bioenergy Statistics* data.

Table B.3 reports the shares of domestic crop consumption value used as livestock feed calculated from the ERS data. Note that we assume all silage production and any hay that is not exported are used as livestock feed, so the feed use shares for hay and silage are equal to one. Each feed use share is multiplied by the value of domestic crop consumption to determine the value of domestic crop consumption used as livestock feed.

The next step is to approximate the state-level value of livestock feed consumption. We use a method developed by Conley, Nagesh, and Salame (2012) to calculate the implied utilization of feed crops in each state based on the state's share of livestock and a index metric called "feed-consuming animal units" (FCAUs) published by ERS in the *Feed Grains Yearbook*. ERS converts livestock inventories to an indexed value, the FCAUs, that can be used to directly compare feed consumption across animal types. For a given category of feed crops, which include grains, high-protein feeds, and roughage, an animal unit is based on the dry-weight quantity of such crops consumed by an average milk cow (Capehart, 2013).[22]

Table B.4 reports the quantities of FCAUs across livestock categories in 2017. These values allow us to compare feed use on a common basis rather than comparing livestock inventories directly. For example, the quantity of feed used by the 2 billion head U.S. poultry sector cannot be easily compared to the feed used by the 14 million milk cows and heifers in the U.S. dairy herd. However, comparing the 10.67 million head of grain-consuming animal units in the dairy sector to the 31.97 million head of grain-consuming

[22]The weights used to construct the index values were initially calculated for a base period of 1969–1971. For more information, see Capehart (2013).

Table B.4: Feed-consuming animal units, 2017 (million head)

Feed type	Dairy	Cattle on feed	Other cattle	Hogs	Poultry	Other livestock	Total
Grains	10.67	20.62	3.62	29.32	31.97	0.62	96.82
High-protein	10.93	11.96	6.24	37.24	83.31	0.50	150.18
Roughage	13.60	2.13	48.74	3.77	0.57	2.11	70.93

Source: USDA/ERS, *Feed Grains Yearbook*.

Note: 2017 FCAUs are calculated from the 2016/17 and 2017/18 marketing years, which run from September through August.

animal units in the poultry sector shows that the poultry industry consumes roughly three times the amount of grain that the dairy industry does.

Following Conley, Nagesh, and Salame (2012), we use state-level livestock data from NASS to calculate the share of each animal type in each state to apportion the national-level FCAUs reported by ERS to the state level. As an example, in 2017 California had about 2.5 million head of dairy cattle, including both milk cows and replacement heifers. This was about 18 percent of the 14.3 million head of dairy cattle across the U.S. The total number of grain-consuming animal units (GCAUs) in 2017 was 96.8 million head, of which about 10.7 million were dairy cattle.[23] We assume that California also accounts for about 18 percent of the dairy GCAUs, meaning about 1.9 million dairy GCAUs were in California. Applying this same method across the other livestock categories, we find that California had a total of 3.8 million GCAUs, or about 4 percent of the total GCAUs for the U.S. This calculation is repeated for high-protein consuming animal units and roughage-consuming animal units to determine the full set of state-level FCAUs.

Once the state-level FCAUs are calculated, the total value of domestic feed crop consumption can be apportioned across states. To determine a given state's value of feed crop consumption, we multiply the state's share of total FCAUs by the U.S. value of domestic feed crop consumption. Continuing with the example of California given above, since California had about 4 percent of total GCAUs, we assume livestock in California consumed 4 percent of the value of domestic feed grain consumption.

The final step is to determine the share of the state-level value of feed crop consumption attributable to the dairy sector. This is accomplished by multiplying the state-level value of feed crop consumption determined in the previous step by the dairy cattle share of the state's FCAUs. For California, the dairy sector accounted for 1.9 million GCAUs out of the

[23] Although the GCAU factor for milk cows is just over 1, the number of dairy GCAUs is less than the dairy cattle inventory because the conversion factor for replacement heifers is about 0.18 (Capehart, 2013).

3.8 million GCAUs total in California. Therefore, approximately half of California's value of feed grain consumption was attributable to the dairy sector. Once we have calculated the state-level value of feed crop consumption by the dairy sector, we aggregate these values across the regions used in our analysis.

Since the FCAUs are only broken down into three feed types, grains, high-protein feeds, and roughage, we use grain-consuming animal units to apportion the value of corn and other grain feed consumption, high-protein consuming animal units to apportion the value of soybeans and other oilseeds consumed as livestock feed, and roughage-consuming animal units to apportion the value of hay consumption. Note that the roughage-consuming animal unit (RCAU) index includes animals consuming pasture. As shown in Table B.4, this results in 48.7 million RCAUs attributed to other cattle (which includes all cattle other than dairy cattle and cattle on feed), 69 percent of the total RCAUs. While it is likely that these cattle are fed some amount of hay, they are also likely to be fed on pasture much more frequently than dairy cattle or cattle on feed. Therefore, our method of utilizing the state-level RCAUs to apportion the value of hay consumption likely underestimates the hay utilized by the dairy sector.

A different procedure is required to determine utilization of silage by the dairy sector. Although we assume all silage production is used entirely as animal feed, we still need to account for the share utilized by the dairy sector.[24] The drawbacks of using the RCAUs apply more acutely for the purpose of determining silage utilization compared to hay utilization, as silage is primarily fed to dairy cattle and beef cattle on feed rather than cattle on pasture. Additionally, the RCAUs account for roughage consumption by hogs, poultry, and other livestock, which consume virtually no silage.

Therefore, we construct the share of silage used in the dairy sector by estimating a regression model with the quantity of silage produced in a state regressed against that state's dairy and cattle on feed, without an intercept. We exclude other livestock sectors from the estimation since corn silage is primarily fed to these types of cattle. The resulting coefficients on dairy and cattle on feed can then be used to calculate the relative share of silage use attributable to each type of cattle. Since we assume silage is not traded between regions, all silage produced in a region is consumed locally and is thus attributable to one of the cattle sectors in that region.

We use data from USDA/NASS on the quantity of silage produced and the number of dairy cattle and cattle on feed in each state. The quantity of silage produced is the sum of corn silage, sorghum silage, and haylage production measured in tons. While sorghum

[24] As explained in Section 3.5, the consequence of apportioning silage between the dairy and other sectors is different than for other feed crops, as dairy silage is assumed to be a different crop than other silage. The share of silage used by the dairy sector is also used to compute the dairy silage cropland share from knowledge of the overall silage cropland share.

silage and haylage are not produced in all states, their production is large relative to corn silage production in some states. The number of dairy cattle includes milk cows and replacement heifers. We use data from 2015 to 2019 to ensure a reasonable approximation of production practices around our reference year of 2017.

To allow for some regional heterogeneity in silage feed intensity, we estimate regional regression models. While the state-based approximations of the FMMO regions would be natural units of analysis, some FMMO regions include only one or two states, limiting the number of observations for those regions. Therefore, we estimate a single regression for a "West" region where California and Arizona are combined with Pacific Northwest, a two-state marketing order region. In addition to the combined West region, we combine Northeast with Appalachian, Southeast with Florida, Upper Midwest with Mideast, and Central with Southwest, resulting in six regions including the Unregulated region. The combined regions use geographically-similar marketing order regions since we are implicitly assuming comparable silage-use patterns.

The results from the regional regressions are shown in Table B.5. We use the estimated regression coefficients together with the 2015–2019 average of cattle numbers to calculate the share of silage use attributable to dairy cattle in each region. The Southeast–Florida combined region has no observed cattle on feed in the NASS data, therefore we assume all silage produced in those regions is used by dairy cattle. The coefficient on cattle on feed in the Northeast–Appalachian combined regression is close to zero and not statistically significant, so we assume all silage is used by dairy cattle in those regions as well. The implied silage use shares are shown in Table B.6.

B.5 Cropland acres and regional land share of the crop dollar

The regional land share of the crop dollar is computed from state-level data on cropland rental rates, total cropland, cropland acres by crop, and the value of crop production by crop. All these data are obtained from USDA/NASS Quick Stats. Data on total cropland, cropland acres, and value of crop production are from the Census of Agriculture and pertain to the reference year 2017. Because cropland rental values by state are based on surveys, and the set of rented acres may vary from year to year, we average reported values over the years 2015–2019.

Regional cropland rental values are computed by multiplying state-level cropland rental rates by state total cropland, summing over states in the region, and then dividing by the sum of state total cropland in the region.

The sum of crop areas for the crops represented in our model (these crops are used to compute the value of crop production and the crop-specific land shares) is lower than the total reported cropland area, but it is generally close. To compute the regional land share of the crop dollar, we multiply the regional cropland rental value calculated above by the sum of the areas of the crops modeled across states in the region, and then divide by the sum of the production values for these same crops across states in the region.

Table B.5: Silage use estimation: regional regression results

	Dependent variable: Silage produced in					
	Northeast-Appalachian	Southeast-Florida	Upper Midwest-Mideast	Central-Southwest	West	Unregulated
	(1)	(2)	(3)	(4)	(5)	(6)
Dairy cattle	12.861^{***}	4.607^{***}	12.136^{***}	6.129^{***}	4.493^{***}	5.742^{***}
	(0.226)	(0.267)	(0.548)	(1.544)	(0.325)	(0.585)
Cattle on feed	0.478		3.312	1.596^{***}	2.382	9.858^{***}
	(3.030)		(2.261)	(0.349)	(1.439)	(1.945)
Observations	80	30	35	50	20	25
F Statistic	$4,370.076^{***}$	297.967^{***}	877.098^{***}	68.971^{***}	614.104^{***}	$1,262.972^{***}$
	(df = 2; 78)	(df = 1; 29)	(df = 2; 33)	(df = 2; 48)	(df = 2; 18)	(df = 2; 23)

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table B.6: Imputed regional silage use (%)

Region	Dairy cattle	Cattle on feed
Northeast	100	0
Appalachian	100	0
Florida	100	0
Southeast	100	0
Upper Midwest	93	7
Central	40	60
Mideast	92	8
California	91	9
Pacific Northwest	80	20
Southwest	64	36
Arizona	68	32
Unregulated	62	38

Source: Regression results in Table B.5 and authors' calculations using data from USDA-NASS.

C Values of selected model elasticities

Table C.1: Elasticities of demand for dairy products by region

Region	Beverages	Softs	Cheese	Butter-Powder
Northeast	-0.43	-0.39	-0.41	-0.47
Appalachian	-0.41	-0.41	-0.42	-0.46
Florida	-0.36	-0.44	-0.42	-0.48
Southeast	-0.38	-0.41	-0.44	-0.47
Upper Midwest	-0.47	-0.46	-0.29	-0.47
Central	-0.43	-0.40	-0.40	-0.47
Mideast	-0.44	-0.38	-0.41	-0.47
California	-0.41	-0.42	-0.43	-0.44
Pacific Northwest	-0.36	-0.44	-0.42	-0.48
Southwest	-0.40	-0.38	-0.44	-0.48
Arizona	-0.36	-0.45	-0.42	-0.47
Unregulated	-0.42	-0.44	-0.37	-0.47
Rest of the World	–	-1.71	-1.56	-1.62

Source: Authors' calculations using Equation (47) with $\epsilon = 0.2$, $\kappa = 0.5$, $\epsilon_0 = 1.3$, and $\kappa_0 = 1.8$.

Table C.2: Regional feed crop demand elasticities

Region	Grains	Oilseeds	Hay	Silage
Northeast	-0.17	-0.18	-0.16	-0.09
Appalachian	-0.17	-0.18	-0.16	-0.09
Florida	-0.16	-0.17	-0.15	-0.12
Southeast	-0.16	-0.18	-0.16	-0.11
Upper Midwest	-0.16	-0.17	-0.15	-0.12
Central	-0.14	-0.16	-0.14	-0.16
Mideast	-0.16	-0.17	-0.15	-0.11
California	-0.15	-0.17	-0.14	-0.14
Pacific Northwest	-0.16	-0.17	-0.15	-0.13
Southwest	-0.14	-0.16	-0.13	-0.16
Arizona	-0.14	-0.17	-0.14	-0.15
Unregulated	-0.15	-0.17	-0.15	-0.13

Source: Authors' calculations using Equation (48) with $\rho = 0.2$.

Table C.3: Regional crop acreage and output elasticities

Region	Grains		Oilseeds		Hay		Silage		Other Crops	
Northeast	[5.64]	0.69	[5.24]	0.56	[4.31]	0.51	[4.43]	0.51	[36.86]	4.56
Appalachian	[3.97]	0.45	[3.03]	0.39	[2.30]	0.23	[2.83]	0.22	[17.21]	2.01
Florida	[5.35]	0.50	[4.49]	0.41	[2.73]	0.24	[3.25]	0.27	[6.85]	2.63
Southeast	[5.61]	0.63	[3.00]	0.46	[1.89]	0.14	[3.06]	0.24	[6.20]	0.74
Upper Midwest	[2.31]	0.30	[2.34]	0.27	[1.77]	0.11	[2.57]	0.19	[2.70]	0.24
Central	[1.82]	0.24	[2.37]	0.25	[1.49]	0.08	[1.24]	0.04	[0.91]	0.02
Mideast	[2.37]	0.30	[1.80]	0.23	[2.14]	0.15	[2.32]	0.16	[7.67]	0.80
California	[2.93]	0.25	[5.95]	0.57	[2.17]	0.17	[1.90]	0.12	[5.20]	1.48
Pacific Northwest	[1.35]	0.10	[16.46]	1.70	[3.11]	0.29	[3.06]	0.24	[3.65]	0.73
Southwest	[5.38]	0.69	[8.11]	1.05	[5.30]	0.60	[7.14]	0.69	[7.30]	0.95
Arizona	[3.43]	0.32	[3.90]	0.39	[3.84]	0.48	[2.33]	0.17	[11.40]	1.77
Unregulated	[2.70]	0.31	[30.73]	3.27	[4.01]	0.47	[8.59]	0.85	[2.81]	0.41

Source: Authors' calculations using Equations (49) and (50) with $\theta = 1.01$ and $\eta = 0.1$. Acreage elasticities are shown in square brackets. Output elasticities are shown without brackets.

Table C.4: Regional milk component demand elasticities

Region	Beverages	Softs	Cheese	Butter-Powder
Northeast	-0.14	-0.24	-0.32	-0.70
Appalachian	-0.36	-0.56	-0.36	-0.25
Florida	-0.13	-0.63	-0.07	-1.06
Southeast	-0.92	-1.26	-1.20	-3.63
Upper Midwest	-0.31	-0.38	-0.63	-0.83
Central	-0.17	-0.27	-0.63	-1.52
Mideast	-0.31	-0.17	-0.74	-4.59
California	-0.11	-0.23	-0.87	-1.55
Pacific Northwest	-0.09	-0.36	-1.00	-3.41
Southwest	-0.17	-0.30	-2.11	-2.03
Arizona	-0.17	-1.49	-1.54	-1.26
Unregulated	-0.12	-0.38	-1.03	-2.19

Source: Authors' numerical simulations of increases in regional milk component prices.

D Sensitivity analysis

Table D.5: Selected results for alternative shape parameter values

Model	Milk production value (%)	Share of milk value shipped (% pt.)	Dairy production value (%)	Dairy export value (%)	U.S. consumer surplus (%)	U.S. land rents (%)	U.S. social welfare (%)	ROW consumer surplus (%)	ROW social welfare (%)
Baseline	-1.56	0.08	-0.17	-0.27	0.17	-0.17	0.123	-0.89	-0.022
$\epsilon_0 = 2.0$, $\kappa_0 = 3.0$	-1.60	0.07	-0.18	-0.88	0.17	-0.17	0.123	-0.88	-0.022
$\varsigma^{\text{bvg.}} = 0.15$, $\varsigma^{\text{softs}} = 0.4$, $\varsigma^{\text{cheese}} = \varsigma^{\text{b-p}} = 0.1$	-1.29	0.15	-0.13	-0.28	0.12	-0.14	0.081	-0.92	-0.023
$\varsigma^{\text{bvg.}} = 0.6$, $\varsigma^{\text{softs}} = 1.6$, $\varsigma^{\text{cheese}} = \varsigma^{\text{b-p}} = 0.4$	-2.05	-0.03	-0.23	-0.24	0.26	-0.21	0.204	-0.80	-0.020
$\rho = 0.5$	-1.52	0.12	-0.16	-0.27	0.16	-0.13	0.123	-0.90	-0.023
$\theta = 1.01$, $\eta = 0$	-1.76	0.13	-0.20	-0.25	0.21	-0.36	0.121	-0.82	-0.021
$\theta = 1.05$, $\eta = 0$	-1.62	0.12	-0.18	-0.26	0.18	-0.23	0.122	-0.87	-0.022
$\theta = 1.1$, $\eta = 0$	-1.55	0.11	-0.16	-0.27	0.16	-0.16	0.123	-0.89	-0.023

Notes: Baseline model has $\epsilon_0 = 1.3$, $\kappa_0 = 1.8$, $\varsigma^{\text{bvg.}} = 0.3$, $\varsigma^{\text{softs}} = 0.8$, $\varsigma^{\text{cheese}} = \varsigma^{\text{b-p}} = 0.2$, $\rho = 0.2$, $\theta = 1.01$, and $\eta = 0.1$. Percentage changes in consumer surplus for the U.S. and the ROW are relative to their respective value of dairy market consumption. Percentage changes in U.S. land rents are relative to the U.S. land rents. Percentage changes in social welfare are relative to the total value of the dairy market, PC.

E Counterfactual increase in farm milk transportation costs

We solve for a variant of the main counterfactual model in relative changes described by Equations (8)–(31). In this variant, we do not alter the component wedges, therefore $\hat{\delta}_i^{nk} = 1$. Instead, we allow the farm milk trade costs τ_{ij} to change by introducing the relative changes $\hat{\tau}_{ij} = K$, with $K > 1$. (Other trade costs are left unchanged.) Equations (20) and (21) are then modified as follows:

$$\left\{\hat{\tau}_{ji}\hat{m}_j - \hat{m}_i \geq 0 \text{ and } \left(\hat{\tau}_{ji}\hat{m}_j - \hat{m}_i\right)\hat{M}_{ji} = 0\right\} \text{ if } \mu_{ji} > 0 \qquad i = 1, \ldots, I, \quad j = 1, \ldots, I \,.$$

$$\hat{M}_i = \sum_{j \geq 1} a_{ij}\hat{\tau}_{ij}\hat{M}_{ij} \qquad i = 1, \ldots, I \,.$$

We then solve the equilibrium model iteratively for increasing values of K until all domestic regions become autarkic in farm milk, that is, $\hat{M}_{ji} = 0$ for all bundles (i, j) such that $i \neq j$ and $\mu_{ji} > 0$. The lowest value of K for which inter-regional trade in farm milk disappears is found to be approximately equal to 1.74, representing a 74% increase in trade costs.