Regional Differences in Food Supply Chain Resiliency: An Equilibrium Displacement Analysis of the US Dairy Industry

Madison Bozich, University of Minnesota, bozic025@umn.edu

Hikaru Peterson, University of Minnesota, hhp@umn.edu

PRELIMINARY DRAFT 5/15/2024: DO NOT CIRCULATE OR CITE

Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

Regional Differences in Food Supply Chain Resiliency

An Equilibrium Displacement Analysis of the US Dairy Industry

May 2024

Abstract

Understanding supply chain resilience is essential in assessing potential threats to and instabilities within US food systems. As global and national agricultural practices have pursued efficiency, increasing integration of supply chains have introduced vulnerabilities that can reverberate across the entire system. The recent COVID-19 pandemic led to tremendous market disruption, from labor shortages to large shifts in retail demand, exposing latent vulnerabilities within US food systems and necessitating an examination of the ways in which supply chains may be analyzed and strengthened. However, the effects of such disruptions were not uniformly felt across the nation; states responded differently, and individual production regions exhibited unique trends not seen on a national scale. To address these challenges and shed light on the dynamics of agricultural resilience, this paper analyzes food chain interactions between regional and national agricultural markets using an Equilibrium Displacement Model (EDM) of the US dairy market. By isolating two primary regional dairy markets, California and the Upper Midwest, relative to surrounding markets, we examine the ways in which disruptions to various supply and demand markets may be felt throughout the larger food system. Furthermore, we explore the pivotal role of more localized food systems in enhancing agricultural resilience and mitigating disruptions. We propose increased diversification of food systems and support for more localized supply chains and a mechanism by which to bolster national agricultural resiliency, applying our model to alternative market structures.

Resilience and US Agriculture

The agricultural landscape of the United States is characterized by an intricate network of supply chains linking producers to consumers across the nation, while simultaneously connecting the US to a larger global food system. Beneath the surface of agricultural integration however lies a complex web of interdependencies. As global and national agriculture practices have become increasingly efficient, potential vulnerabilities have also emerged, necessitating a closer examination of the strength of supply chains. Notably, the enhancement of supply chain efficiency has concurrently heightened their vulnerability to extensive disruptions (Hobbs, 2021; Applebaum and Gaby-Biegle, 2020; Hendrickson, 2015). Unlike more decentralized networks where disruptions in one sector may be contained, the highly integrated nature of modern agricultural supply chains amplifies the impact economic distortions. A breakdown at any point along the chain, whether due to natural disasters, geopolitical tensions, or unforeseen market shifts, can send shock-waves throughout the entire system. While the pursuit of efficiency has undoubtedly yielded benefits, it has also introduced a degree of rigidity into the system, potentially weakening resilience.

Particularly following the COVID-19 pandemic, there has been increased attention given to the security and strength of agricultural supply chains (Barman et al., 2021; Hobbs, 2020). Recent calls from the Biden administration have directed agencies across the US to examine potential faults in US agriculture and areas for improvement moving forward (USDA, 2022), while globally policymakers have sought out mechanisms by which to increase supply chain resiliency (USDA, 2022; FAO, 2021). With COVID-19, the agricultural system was upturned by a sudden shifts in demand from food service, consumer demand at the retail level, labor shortages, preference changes, and other pandemic restrictions, as the US grappled with a series of shutdowns. These multi-faceted disruptions underscored multiple latent vulnerabilities within US agricultural supply chains, heightening concerns for market stability moving forward. Resilience within the agricultural system, defined as the ability to maintain core functionality amidst external disruptions, is shaped by multiple critical dimensions, including the diversity of the food system and the interconnectedness of its components (Rotz and Fraser, 2015). Yet, the exact relationship between resilience and current efficiency-focused supply chain structures structures have not been well-researched (Hobbs, 2021), and there are few economic models which allow for a concise and generalized evaluation of agricultural resilience. Understanding and fortifying supply chain resilience demands a thorough examination of the ability of a food system to withstand shocks and adapt to evolving conditions.

A primary issue surrounding food system resiliency is the propensity of singular shocks along elements of supply chains to successively impact multiple subsequent markets. Developing robust models to quantify these interactions is imperative for comprehending the intricacies of the food system and identifying strategic intervention points to bolster resilience. However, it is difficult to gauge the impact of certain regional movements upon supply chains nationally; there does not exist a mechanism by which to examine how food systems robustly interact with one another. Comprehensively analyzing these impacts requires an integrated model of agricultural industries, and their ties to one another; emphasizing the interactions between markets in order to isolate the effects of industry structures on supply chain resilience. This task is further complicated by the intricate interplay between local and national dynamics.

However, it is an increased emphasis upon more localized supply chains and support for local markets functioning within the larger food system which may have the potential to reduce reliance upon larger and more highly integrated supply chains (Anggraeni et al., 2022; Ryan et al., 2024). While there is no singular definition of local food systems, they are broadly described as "collaborative networks that integrate sustainable food production, processing, distribution, consumption and waste management in order to enhance the environmental, economic and social health" of a region (Feenstra and Campbell, 2014). For the purposes of our model and results, references to locality are describing larger regional production hubs. Although relatively large compared to direct to consumer supply chains, production regions which function with a larger degree of independence from larger food systems may be shielded from disruptions in national and global supply dynamics, maintaining the resilience of the system overall with a series of smaller food support systems.

In recent years demand for local foods across a multitude of channels has increased. Consumers have taken an increasing interest in the source and origin of the food they purchase, while increasingly expressing preferences for local and sustainable products, with an emphasis upon product quality (Fang et al., 2018; Enthoven and Van Den Broeck, 2021; Feenstra and Hardesty, 2016; Merlino et al., 2022). On the institutional end, there has been an enhanced emphasis upon providing support for local farms, farming communities, and the promotion of healthier eating bolstered by collaboration with local food systems. These serve as an alternative to conventional supply chains, and increase the stability and functionality of food systems overall. Thus, strengthening the independence of local food systems has been proposed as one mechanism by which to bolster otherwise brittle supply chains (Anggraeni et al., 2022). Local integration further provides an opportunity for smaller farmers and producers of more differentiated agricultural products to participate in a food system which otherwise favors large scale production and integration. Emphasis upon local production may also reduce to an extent the environmental impact of non-local production which must then be distributed nationally and globally (Brodt et al., 2013). However, while preferences for local food may be on the rise, and stronger local food systems may function to strengthen brittle supply chains, the ways in which local supply chains function and interact within the larger food system are not well understood.

In this paper, we develop a general equilibrium displacement model (EDM) for US agricultural sectors, encompassing the farm, processing, and retail levels with an additional distinction made between a designated region and the rest of the country. For our analysis, dairy was chosen as the commodity of interest. Organized into Federal Milk Marketing Orders (FMMOs), the dairy industry is highly regionalized at the farm level. Perishability and bulkiness of raw milk further limits and localizes the processing of dairy commodities, while differences in large dairy production regions differentiate market structure regionally. Thus, dairy was chosen to emphasize the potential application of an EDM which may robustly account for interconnected yet distinct markets. Primarily, this model functions to demonstrate the impacts of changing the levels of integration between smaller regional and larger non-regional supply chains. Dairy was further a sector highly impacted by COVID-19, on both the supply and demand side. The initial pandemic shock resulted in trade disruptions, as well as food-service and institutional closures which drastically impacted demand for various dairy products. From here, panic buying changed the product mix demanded at the retail end, which eventually collapsed as excess demand subsided. Additional ripple effects and government intervention further destabilized pre-pandemic dairy supply and demand (Acosta et al., 2021). Demand impacts were widely felt, particularly in response to disruptions caused by the pandemic (Cranfield, 2020). Additional behavioral changes prompted increased attention of household consumers to nutritional value and the healthfullness of meals (Chen et al., 2024). Thus, dairy in the context of COVID-19 represents a market via which our model functionality may be tested across a multitude of specifications.

As a result of the interactions allowed between different supply chains, this model allows for the estimation of regionally differentiated impacts caused by the COVID-19 on the dairy market. The impact of restaurant closures is specified as a perturbation of the food-service component of the retail layer to the model in conjunction with changes to consumer demand for FAH and FAFH. Government support programs are modeled as increases in government spending at the upstream processing level of the model, to determine how government assistance affected the entire dairy supply chain and what may have happened in its absence. Additional analysis will emphasize the disconnects between production regions, and what market structures support agricultural resilience. Regional and national integration may be modeled by changing existing substitution elasticities between regional and non-regional inputs, while shifts in consumer preferences are modeled via changes to the food at home and food away from home sector's willingness to substitute between local and non-local commodities. When analyzing market disruptions due to the pandemic, these series of changes may be compared to the baseline model to demonstrate how potential changes to regional and national integration may impact the severity of market disruptions, in addition to more traditional policy analysis. This complete analysis allows for a robust assessment of the impact of COVID-19 upon food systems in the United States, as well as the ways in which interruptions to local supply chains may impact national production and consumption of agricultural products. Furthermore, hypothetical policy scenarios will shed light on the ways in which alternative action may have mitigated supply chain disruptions arising as a result of the pandemic.

Overall, we present a detailed examination of the breakdown to regional and national supply chains that occurred due to the pandemic, with a focus upon US dairy markets. The rich series of interactions between market types within the constructed EDM will isolate sectors of the dairy supply and demand chains which are particularly vulnerable to market distortions, as well as those which are well situated to withstand large shocks. Additionally, we apply this model to hypothetical market setups where the strength and independence of local agricultural systems has been cultivated, the demonstrate the ways in which disaggregated agricultural practices may straighten resilience of the system as a whole. Applications of the baseline EDM suggest that government support programs function more effectively upstream at the farm level, and may exacerbate downstream economic disruption if not targeted appropriately. Resilience analysis comparing the relatively elastic structure of Upper Midwest markets to dairy production in California indicate that a more flexible local production structure results in smaller overall economic disruptions when compared to larger, more specialized dairy operations. However, isolating resilient structures downstream becomes somewhat muddier, depending on the local preferences within a region. The incorporation of parameters differentiating processed dairy commodities into those destined for commercial vs. household purposes may help isolate the impact of disruptions to FAH vs. FAFH. Finally, reliance upon a few large production regions does leave the larger food system at increased risk of economic disruption; despite the strength of the region itself. A more rigid national food system is not well equipped to handle large economic distortions.

While the current application examines the consequences of COVID-19 with respect to dairy, the construction of a nuanced EDM allowing for increased integration between two production regions provides a framework by which to analyze other industries. Ideally, this may reveal ways in which supply chains overall, both regionally and nationally, may be strengthened.

Literature

There has been a great deal of work examining the various supply chains in the United States, as well as changes to the structure of the agricultural landscape. In this same vein, much work has been dedicated to an examination of the resilience of supply chains. However, there is less literature focusing on the general examination of supply chains; particularly with respect to how they interact with one another.

Following the pandemic, a strand of literature has studied the impacts of COVID-19 upon dairy markets. Acosta et al. (2021) and Duan et al. (2022) examined the impacts of COVID-19 on the development of global dairy markets. Other work has focused specifically on US supply chains (Wolf et al., 2021; Weersink et al., 2021; Wang et al., 2020). Liu and Rabinowitz (2021) specifically research COVID-19 and retail dairy prices, while Applebaum and Gaby-Biegle (2020) discuss the ways in which dairy industry consolidation may have left the sector particularly vulnerable. There remains a gap in understanding the nuanced interplay between regional and national disruptions within the dairy sector. We build upon the existing work, to examine the extent to which national and regional fluctuations to supply and demand chains interact.

This study builds upon existing research by employing an equilibrium displacement model to analyze the differential impacts of COVID-19 on dairy markets at both regional and national levels. By focusing on two major production regions, the Minnesota-Wisconsin region (MN-WI) and California, we seek to unravel the distinct repercussions of pandemic-induced disruptions and their cascading effects across supply chains.

Model

We develop an equilibrium displacement model of the US dairy industry, with an explicit focus upon regional and non-regional (referred to henceforth as national for simplicity) market interactions. Three primary market segments are considered; a farm sector, a processing sector, and a retail sector. At the farm and processing levels, we distinguish between regional and national components of supply and demand, including inputs to the production process. This allows us to distort regional prices relative to national prices and examine the ways in which disruptions to specific sectors spillover into others. Three commodities are produced in the manufacturing sector of the model to be sold to the retail sector: fluid milk, butter, and cheese. Finally, the retail portion of the model considers an at home and an away from home consumption sector. This distinction allows us to manipulate demand for food at home (FAH) and food away from home (FAFH) and mimic the ways in which pandemic shutdowns influenced dairy demand. We also allow for shifts in demand due to regional/national price changes, FAH and FAFH expenditures overall, and SNAP allotments

California and Wisconsin, and by extension the Upper Midwest, are the two largest dairy production regions in the United States (de Witte et al., 2010). Generally, the size of farms in California exceed those in Wisconsin, with a majority of Western firms having herd sizes over 1000 with high levels of density, while dairies in WI tend to be below 300 heads. Additionally, dairy production in California tends to be more highly specialized, while farms in Wisconsin derive income from additional sources (de Witte et al., 2010). There are disconnects in perceived issues facing these farms in the future as well, with farms in California more concerned about environmental regulations and resource availability, while those in the Midwest worried proportionately more about labor availability and family farm situations, as well as animal disease (de Witte et al., 2010). In our application, we examine how the markets in these two contrasting regions interact with the national markets.

Regional elasticities are adjusted wherever possible to account for differences between California, MN-WI, and the remainder of production in the US. Shocks in two of the largest production regions, the two-state Minnesota-Wisconsin region (MN-WI) and California, are examined separately in conjunction with the nation as a whole. Both regions are essential to the production of raw milk and processed dairy products. COVID-19 disruptions to either of these regional or national sectors will thus have effects distinct from one another, that interact throughout the chains of supply and demand. Therefore, the regional-national distinction proposed allows for a more nuanced examination of economic disruptions, as well as the ways in which regional disruptions may affect non-regional supply and demand.

Variables

Table 1: Variables

Local	Non-Local	Description
Q_{lf}^{fluid}	Q_{nlf}^{fluid}	Farm milk quantities
P_{lf}^{fluid}	P_{nlpf}^{fluid}	Price of farm milk
P_{lf}^{feed}	P_{nlpf}^{feed}	Price of farm feed
Q_{lp}^{fluid}	Q_{nlp}^{fluid}	Quantity of fluid milk
P_{lp}^{fluid}	P_{nlp}^{fluid}	Price of fluid milk
$P_{lp,I}^{fluid}$	$P_{nlp,I}^{fluid}$	Price of Class I milk for fluid milk production
$P_{lp,labor}^{fluid}$	$P_{nlp,labor}^{fluid}$	Price of labor for fluid milk production
Q_{lp}^{butter}	Q_{nlp}^{butter}	Quantity of butter
P_{lp}^{butter}	P_{nlp}^{butter}	Price of butter
$P_{lp,I}^{butter}$	$P_{nlp,I}^{butter}$	Price of Class III milk for butter production
$P_{lp,butter}^{butter}$	$P_{nlp,labor}^{butter}$	Price of labor for butter production
Q_{lp}^{cheese}	Q_{nlp}^{cheese}	Quantity of cheese
P_{lp}^{cheese}	P_{nlp}^{cheese}	Price of cheese
$P_{lp,I}^{cheese}$	$P_{nlp,I}^{cheese}$	Price of Class IV milk for cheese production
$P_{lp,labor}^{cheese}$	$P_{nlp,labor}^{cheese}$	Price of labor for cheese production

Model Construction

Comprehensively, the model covers the farm, processing, and retail sectors for three commodities; fluid milk, butter, and cheese. Each sector is structured analogously, with industry specific elasticity and parameter values.

Farm

Demand for farm milk regionally and nationally is the sum of processing demand locally and nationally for raw milk. We allow non-regional processors to purchase milk from regional farms, and visa-versa, at the farm milk price:

$$Q_{lf}^{milk} = ffl_1 Q_{lp}^{fluid} + ffl_2 Q_{nlp}^{fluid} \tag{1}$$

$$Q_{nlf}^{milk} = nffl_1 Q_{lp}^{fluid} + nffl_2 Q_{nlp}^{fluid} \tag{2}$$

Supply of farm milk is dependent upon feed costs as well as the blend price of milk within a region:

$$Q_{lf}^{fluid} = f_1(P_{lf}^{feed}, P_{lf}^{fluid}) \tag{3}$$

$$Q_{nlf}^{fluid} = f_2(P_{nlf}^{feed}, P_{nlf}^{fluid}) \tag{4}$$

We parameterize the blend price of milk as a weighted average of milk class prices for the commodities of interest; covering class I, class III, and class IV. Due to the nature of Federal Milk Markets Orders (FMMOs), these weighted averages are taken within their respective region.

$$P_{lf}^{fluid} = \frac{P_{lp}^{class\ 1} Q_{lp}^{class\ I} + P_{lp}^{class\ IV} Q_{lp}^{class\ IV} + P_{lp}^{class\ III} Q_{lp}^{class\ III}}{Q_{lp}^{class\ I} + Q_{lp}^{class\ III} + Q_{lp}^{class\ IV}} \tag{5}$$

$$P_{nlf}^{fluid} = \frac{P_{nlp}^{class\ 1} Q_{nlp}^{class\ I} + P_{nlp}^{class\ IV} Q_{lp}^{class\ IV} + P_{nlp}^{class\ III} Q_{lp}^{class\ III}}{Q_{nlp}^{class\ I} + Q_{nlp}^{class\ III} + Q_{nlp}^{class\ IV}} \tag{6}$$

Processing

As with the farm sector, the total demand for a commodity at the processing sector is a sum of the downstream commodity demands for that product. In this case, we cover demand for a commodity from consumer retail and food-service, while considering demand from within and outside the region of interest:

$$Q_{lp}^{fluid} = fl_1 Q_{lc}^{fluid} + fl_2 Q_{lr}^{fluid} + fl_3 Q_{nlc}^{fluid} + fl_4 Q_{nlr}^{fluid} \tag{7}$$

$$Q_{nlp}^{fluid} = nfl_1 Q_{lc}^{fluid} + nfl_2 Q_{lr}^{fluid} + nfl_3 Q_{nlc}^{fluid} + nfl_4 Q_{nlr}^{fluid} \tag{8}$$

Here, the supply of milk at the processing level is a function of the commodity price, labor costs, and milk class input costs. Currently, the model limits input sourcing to the regional level.

$$Q_{lp}^{fluid} = f_3(P_{lp}^{fluid}, P_{lp,labor}^{fluid}, P_{lp,class\ I}^{fluid}) \tag{9}$$

$$Q_{nlp}^{fluid} = f_4(P_{nlp}^{fluid}, P_{nlp,labor}^{fluid}, P_{nlp,class\ I}^{fluid}) \tag{10}$$

Pricing for the processing price of each commodity depends upon the input prices and their costs shares; in this model this encompasses labor and milk class inputs:

$$P_{lp}^{fluid} = K_{1,l}^{fluid} P_{lp}^{class\ I,D} + K_{2,l}^{fluid} P_{lp}^{labor,D} \tag{11}$$

$$P_{nlp}^{fluid} = K_{1,nl}^{fluid} P_{nlp}^{class\ I,D} + K_{2,nl}^{fluid} P_{nlp}^{labor,D} \tag{12}$$

Quantities demanded for labor and milk class inputs are functions of their prices:

$$Q_{lp}^{class\ I} = f_5(P_{lp}^{class\ I,S}), \quad Q_{nlp}^{class\ I} = f_6(P_{nlp}^{class\ I,S}) \tag{13}$$

$$Q_{lp}^{labor} = f_7(P_{lp}^{labor,S}), \quad Q_{nlp}^{labor} = f_8(P_{nlp}^{labor,S}) \tag{14}$$

Retail

Overall, the retail section is split into two components, a consumer retail and a food-service sector. This division allows us to specify specific components of demand to mirror what happened during the pandemic in our analysis, where consumption habits were radically changed by shifts in food access. Households do not uniformly consume dairy across FAH and FAFH; a majority of fluid milk consumption occurs at home, while proportionally more butter and cheese consumption occurs at FAFH (Wolf et al., 2021). Additionally, this division allows us to draw a distinction between how both sectors operate. Within our model, we parameterize the consumer retail sector as generally more elastic than the restaurant sector. Households are considered to be more flexible in their purchasing than restaurants, who would need to update fixed menus and recipes in response to all price changes. Looking ahead, this division will allow us up to draw a distinction between the types of products purchased by consumers. Accentuated as an issue during the pandemic, supply chains for commercial sale often produce bulk products which are not appropriate for at home purchase. Similarly, chains set up to provide household-sized products are ill-equipped to supply restaurants with the necessary products at commercial scale.

Quantities demanded at the consumer retail level are functions of the local and non-local commodity prices; allowing consumers to have preferences over regionally vs. non-regionally sourced products. Quantity demanded further depends on overall household food expenditures, SNAP benefits, and the prices of other dairy products at the retail level:

$$Q_{lc}^{fluid} = f_8(P_{lc}^{fluid}, P_{nlc}^{fluid}, P_{lc}^{cheese}, P_{lc}^{butter}, X_{lc}^{expenditures}, X_{lc}^{SNAP}) \tag{15}$$

$$Q_{nlc}^{fluid} = f_8(P_{nlc}^{fluid}, P_{lc}^{fluid}, P_{lc}^{cheese}, P_{lc}^{butter}, X_{nlc}^{expenditures}, X_{nlc}^{SNAP}) \tag{16}$$

The food-service sector demand functions similarly, except quantities are dependent upon the prices of FAFH as opposed to total food expenditures and SNAP benefits. Again, we allow for interactions between national and regional markets.

$$Q_{lr}^{fluid} = f_9(P_{lc}^{fluid}, P_{nlc}^{fluid}, P_{lc}^{cheese}, P_{lc}^{butter}, X_{lc}^{FAFH}) \tag{17}$$

$$Q_{nlr}^{fluid} = f_10(P_{nlc}^{fluid}, P_{lc}^{fluid}, P_{lc}^{cheese}, P_{nlc}^{butter}, X_{nlc}^{FAFH}) \tag{18}$$

In simulations below, changes to FAH and FAFH purchasing is modeled by perturbing the demand for dairy from the consumer and food-service sectors. The baseline simulation increases the quantity demanded for at home dairy consumption by 10%, while decreasing demand for food-service dairy by 15%. When emphasizing a region, e.g., California relative to the United States, these distortions are increased by 5% each. Within the traditional EDM testing, there is a baseline disruption for each industry, with specific simulations emphasizing distortions either regionally or nationally. In the resilience analysis, these impacts are isolated; one region will be impacted while the other is not.

Empirical Application

Traditional EDM Application

For the first application of the model, we use our baseline model and run simulations based on disruptions to the consumer retail and food-service sectors. With this application, we may analyze different retail distortions mimicking the economic disturbances felt during the COVID-19 pandemic. In our initial trials, we perturb consumer and food-service expenditures analogously across sectors; distortions are of the same magnitude in nationally and regionally. For the following two trials we again perturb retail demand, however we begin by first distorting the national sector by an additional 5% relative to the local sector, then by perturbing regional sectors by an additional 5% when compared to national demand shifts. This allows us to isolate the ways in which local and national disturbances function both in conjunction and opposite one another, and which portions of the supply chain are most vulnerable to economic disturbance.

Following the baseline application, we then re-run our preceding three simulations, now with the addition of government support at the commodity processing level. With this trial, we attempt to isolate the impact of direct government commodity support, and to which aspects of the supply and demand chains is this support most beneficial. Results are presented for a portion of the full specification using California parameters. Additional details for butter and cheese are in the appendix.

This first set of results (Table 2) presents three trials using at the farm level. Each sector; dual, national, and regional, present a different set of economic distortions broadly mirroring demand disruptions to dairy as a result of the pandemic. In the dual movement trials, distortions to national and regional demand have the same magnitude. In the national trials, national distortions

Table 2: Results - California Farm

Variable	Dual	Dual + Govt.	Natl.	Natl. + Govt.	Region	Region + Govt.
Q^S_{lf}	0.140	0.100	0.237	0.198	0.140	0.100
Q^S_{nlf}	0.001	-0.066	0.039	-0.029	-0.019	-0.087
P_{lf}	0.606	0.434	1.028	0.856	0.605	0.433
P_{nlf}	0.003	-0.181	0.106	-0.078	-0.053	-0.238
Q^D_{lf}	-0.027	-0.010	-0.050	-0.033	-0.024	-0.007
Q^D_{nlf}	-0.025	-0.007	-0.048	-0.030	-0.022	-0.004

domination regional distortions. Finally, in the regional component of the simulation, the regional demand disruptions are taken to have a higher magnitude than national distortions. After each trial, and additional simulation is run under the scenario where the government makes direct commodity purchases nationally and regionally at the processing level in order to support dairy supply.

In the first trial where there are proportional regional and national distortions to the demand for fluid milk, direct support at the processing level does not uniformly reduce the magnitude of distortions. At the regional level, within California, the direct support helps across the board. However, the payments result in relatively larger national price and supply movements for farm milk.

Looking at national and regional movements and support scenarios, the trend is more clear. Dairy support when national distortions dominate regional distortions across the board temper the impacts of the demand shifts. At the regional level, support does support resilience in California relative to the scenario without support, however it results in larger national price and quantity movements.

Looking more broadly at the processing and retail sectors follows a far different pattern than that at the farm sector. Government payments in response to changes in demand for retail and food-service dairy aggravates economic disruptions. This may be due to the downstream structure for fluid milk. Generally, food-service is less price elastic than the consumer retail sector. Thus, when there is a simultaneous decrease in demand for dairy from the food-service sector coupled with a spike in demand for household dairy expenditures, the demand increase from the consumer end

Table 3: Results - California Fluid Milk

Variable	Dual	Dual + Govt.	Natl.	Natl. + Govt.	Region	Region + Govt.
Q_{lp}^{fluid}	0.050	0.107	0.038	0.095	0.077	0.134
Q_{nlp}^{fluid}	0.060	0.117	0.054	0.110	0.088	0.145
$P_{lp}^{fluid,D}$	-0.191	-0.409	-0.145	-0.362	-0.295	-0.513
$P_{nlp}^{fluid,D}$	-0.207	-0.402	-0.185	-0.380	-0.304	-0.499
$P_{lp}^{fluid,S}$	-0.191	-0.409	-0.145	-0.362	-0.295	-0.513
$P_{nlp}^{fluid,S}$	-0.207	-0.402	-0.185	-0.380	-0.304	-0.499
$Q_{lp}^{class\ I}$	0.050	0.107	0.038	0.095	0.077	0.134
$Q_{nlp}^{class\ I}$	0.060	0.117	0.054	0.110	0.088	0.145
$P_{lp}^{class\ I}$	-0.560	-1.198	-0.425	-1.063	-0.865	-1.504
$P_{nlp}^{class\ I}$	-0.607	-1.180	-0.543	-1.116	-0.891	-1.463
Q_{lc}^{fluid}	0.126	0.186	0.100	0.160	0.200	0.259
Q_{nlc}^{fluid}	-0.064	-0.500	0.150	-0.285	-0.219	-0.655
Q_{lr}^{fluid}	-0.217	-0.232	-0.243	-0.258	-0.329	-0.344
Q_{nlr}^{fluid}	-0.109	-0.104	-0.190	-0.185	-0.103	-0.098

may dominate the negative pressure from the restaurant sector shut down. Government purchases at the processing level further aggregate the issues, raising prices and leading to larger economic disruption on aggregate. Incorporating heterogeneity in the commodities produced at the processing level may help temper this. The current model treats all processed dairy as a uniform product which is interchangeable for use in consumer retail or food-service. In reality, dairy manufacturing is often set up for consumer or commercial use. Drawing this distinction and directing government support towards processes specializing in commercial production would then be expected to have a tempering effect, as opposed to one exacerbating demand spikes.

Supply Chain Resilience Analysis

With the second application of this model we examine supply chain resilience between two regions, with an emphasis upon the ways in which greater regional production flexibility may mitigate economic distortions. Here we present results for two regions, California and the Upper Midwest. Primarily, this version of the analysis isolates how production and processing structures differentiate two regions. Within this construction, California is taken to be more highly integrated and concentrated into larger supply chain networks, while the Upper Midwest contains a higher number of small to medium sized firms, which may more easily supply local goods within the region.

As with the traditional model application, we compare regional responses for California and the Upper Midwest to modest changes in demand for consumer retail and food-service dairy products. In the first simulation, only the local region is impacted by a fall in demand for dairy from food-service, following by an increase in demand for retail dairy. In the second trial the trend is reversed, and there are only surrounding demand distortions. Finally, the last trial presents the case where there are both supply and demand distortions of equal magnitude within the national and regional sectors.

Table 4: CA vs. UM Resilience Comparison - Farm

Variable	Regional CA	Regional UM	National CA	National UM	Dual CA	Dual UM
Q^S_{lf}	-0.022	-0.015	0.259	-0.010	0.237	-0.031
Q^S_{nlf}	-0.056	0.069	0.095	0.034	0.018	0.150
P_{lf}	-0.095	-0.061	1.123	-0.043	1.027	-0.128
P_{nlf}	-0.154	0.190	0.260	0.094	0.049	0.412
Q^D_{lf}	0.011	-0.004	-0.061	-0.001	-0.047	-0.009
Q^D_{nlf}	0.012	-0.006	-0.060	-0.002	-0.045	-0.013

In general, the Upper Midwest has a less aggregated production structure when compared to California. Dairy operations tend to be smaller and more numerous, with farmers garnering income from multiple source as opposed to strictly dairy (de Witte et al., 2010). Additionally, figures from literature support the Upper Midwest as a generally more elastic region than California when it comes to production practices. Comparing results from the above trials at the farm level with isolated regional or national movements, the structure of the Upper Midwest is generally more resilient to economic distortions than California. With dual movements the structure of the Upper Midwest results in more national distortions than regional disruption, while results from the California simulation predict higher disruptions within the California region than the rest of the nation. To some extent, these results are also due to the split of dairy commodities produced as exported. With respect to fluid milk, California consumes more of their production within-region than the Upper Midwest does. Thus, changes to the upper Midwest will have a larger impact on national supply chains. However, the flexibility of the Upper Midwest produces more resilient estimates within-region than those predicted using California parameters.

Table 5: CA vs. UM Resilience Comparison - Fluid Milk

Variable	Regional CA	Regional UM	National CA	National UM	Dual CA	Dual UM
Q_{lp}^{fluid}	0.058	-0.057	-0.020	-0.025	0.065	-0.119
Q_{nlp}^{fluid}	0.059	-0.029	-0.005	-0.015	0.082	-0.064
$P_{lp}^{fluid,D}$	-0.221	0.178	0.076	0.077	-0.249	0.371
$P_{nlp}^{fluid,D}$	-0.204	0.100	0.019	0.051	-0.282	0.221
$P_{lp}^{fluid,S}$	-0.221	0.178	0.076	0.077	-0.249	0.371
$P_{nlp}^{fluid,S}$	-0.204	0.100	0.019	0.051	-0.282	0.221
$Q_{lp}^{class\ I}$	0.058	-0.057	-0.020	-0.025	0.065	-0.119
$Q_{nlp}^{class\ I}$	0.059	-0.029	-0.005	-0.015	0.082	-0.064
$P_{lp}^{class\ I}$	-0.648	0.522	0.223	0.226	-0.730	1.089
$P_{nlp}^{class\ I}$	-0.598	0.294	0.055	0.150	-0.827	0.648
Q_{lc}^{fluid}	0.149	0.003	-0.049	-0.027	0.174	-0.028
Q_{nlc}^{fluid}	-0.369	-0.081	0.519	0.109	-0.004	0.011
Q_{lr}^{fluid}	-0.174	-0.190	-0.069	-0.002	-0.355	-0.310
Q_{nlr}^{fluid}	0.011	0.061	-0.201	-0.232	-0.184	-0.136

Comparing California to the Upper Midwest at the processing and retail levels yields somewhat different conclusions than those from the farm sector. While the structure of farming and processing may be more flexible in the Upper Midwest than in California, adding in the retail component tempers to some extent the previously observed resilience. When isolating regional movements, the Upper Midwest simulation results in slightly less distortion than the results from California, taken at absolute value. Results are less clear looking at national and dual movements, as the structure of the Upper Midwest and California are less clearly distinguished downstream.

Conclusions

Overall, this model provides a general mechanism by which to isolate national and regional disruptions. When isolating traditional EDM movements, we can isolate which regions are the most and least impacted by supply chain disruptions, as well as which sectors may be shielded relative to others. Broadly, government support measures via direct commodity purchasing at the processing level have the greatest benefit at the farm and upstream processing sectors. At the retail level, direct support exacerbates economic disruptions. However, this may be attributed to the uniform treatment of commodities at the processing level. Incorporating disconnect in dairy products intended for commercial vs. retail use could demonstrate more effective measures by which direct support purchases may be instituted. When analyzing resilience, initial model results accentuate the differences between relatively elastic and relatively inelastic markets; with the Upper Midwest demonstrating greater degrees of resilience than California. This accentuates to some extent the impact of consolidation supply chain concentration; as production in the Upper Midwest is generally smaller and less specialized than farm operations in California. However, which the structure of the Upper Midwest be better equipped to handle economic disruptions, reliance of national markets on such a large production region leaves the larger food system vulnerable to regional disruptions.

References

A. Acosta, S. McCorriston, F. Nicolli, E. Venturelli, U. Wickramasinghe, E. ArceDiaz, L. Scudiero, A. Sammartino, F. Schneider, and H. Steinfeld. Immediate effects of COVID-19 on the global dairy sector. *Agricultural Systems*, 192:103177, Aug. 2021. ISSN 0308521X. doi: 10.1016/j.agsy.2021.103177. URL `https://linkinghub.elsevier.com/retrieve/pii/S0308521X2100130X`.

E. W. Anggraeni, Y. Handayati, and S. Novani. Improving Local Food Systems through the Coordination of Agriculture Supply Chain Actors. *Sustainability*, 14(6):3281, Mar. 2022. ISSN 2071-1050. doi: 10.3390/su14063281. URL `https://www.mdpi.com/2071-1050/14/6/3281`.

E. Applebaum and J. Gaby-Biegle. Spilt Milk: COVID-19 and the Dangers of Dairy Industry Consolidation. *Institute for New Economic Thinking Working Paper Series*, pages 1–30, Aug. 2020. doi: 10.36687/inetwp134. URL `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3731831`.

A. Barman, R. Das, and P. K. De. Impact of COVID-19 in food supply chain: Disruptions and recovery strategy. *Current Research in Behavioral Sciences*, 2:100017, Nov. 2021. ISSN 26665182. doi: 10.1016/j.crbeha.2021.100017. URL `https://linkinghub.elsevier.com/retrieve/pii/S2666518221000048`.

S. Brodt, K. J. Kramer, A. Kendall, and G. Feenstra. Comparing environmental impacts of regional and national-scale food supply chains: A case study of processed tomatoes. *Food Policy*, 42:106–114, Oct. 2013. ISSN 03069192. doi: 10.1016/j.foodpol.2013.07.004. URL `https://linkinghub.elsevier.com/retrieve/pii/S0306919213001012`.

J. Chen, C.-C. Yang, and Y. Lin. Effects of the COVID-19 Pandemic on Dairy Consumption Trends: An Empirical Investigation of Accounting Data in China. *Foods*, 13(5):741, Feb. 2024. ISSN 2304-8158. doi: 10.3390/foods13050741. URL `https://www.mdpi.com/2304-8158/13/5/741`.

J. A. L. Cranfield. Framing consumer food demand responses in a viral pandemic. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 68(2):151–156, June 2020. ISSN

0008-3976, 1744-7976. doi: 10.1111/cjag.12246. URL https://onlinelibrary.wiley.com/doi/10.1111/cjag.12246.

C. Davis, D. Dong, D. Blayney, and A. Owens. An Analysis of U.S. Household Dairy Demand. Technical Bulletin 1928, United States Department of Agriculture Economic Research Service, Dec. 2010.

A. de Witte, J. Nowak, F. Schierholz, and B. Lassen. Dairy farming in Wisconsin and California: Different challenges – different future? Technical report, Agri benchmark & the European Dairy Farmers, 2010.

W. A. Donnelly, K. Johnson, and M. Tsigas. Revised Armington Elasticities of Substitution for the USITC Model and the Concordance for Constructing a Consistent Set for the GTAP Model. 2004.

Y. Duan, Q. Lai, S. Li, Z. Liu, and C. Yang. Analysis of the Development of the Dairy Industry During COVID-19:. Wuhan, China, 2022. doi: 10.2991/aebmr.k.220405.064. URL https://www.atlantis-press.com/article/125973767.

L. Enthoven and G. Van Den Broeck. Local food systems: Reviewing two decades of research. *Agricultural Systems*, 193:103226, Oct. 2021. ISSN 0308521X. doi: 10.1016/j.agsy.2021.103226. URL https://linkinghub.elsevier.com/retrieve/pii/S0308521X21001797.

X. Fang, H. Huang, and P. Leung. Competitiveness of local food: an empirical analysis of the tomato market dynamics. *International Food and Agribusiness Management Review*, 21(1):89–100, Jan. 2018. ISSN 1559-2448. doi: 10.22434/IFAMR2016.0139. URL https://brill.com/view/journals/ifam/21/1/article-p89_6.xml.

FAO. *The State of Food and Agriculture 2021*. FAO, Nov. 2021. ISBN 978-92-5-134329-6. doi: 10.4060/cb4476en. URL http://www.fao.org/documents/card/en/c/cb4476en.

G. Feenstra and D. C. Campbell. Local and Regional Food Systems. In P. B. Thompson and D. M. Kaplan, editors, *Encyclopedia of Food and Agricultural Ethics*, pages 1345–1352.

Springer Netherlands, Dordrecht, 2014. ISBN 978-94-007-0928-7 978-94-007-0929-4. doi: 10.1007/978-94-007-0929-4_73. URL http://link.springer.com/10.1007/978-94-007-0929-4_73.

G. Feenstra and S. Hardesty. Values-Based Supply Chains as a Strategy for Supporting Small and Mid-Scale Producers in the United States. *Agriculture*, 6(3):39, Aug. 2016. ISSN 2077-0472. doi: 10.3390/agriculture6030039. URL http://www.mdpi.com/2077-0472/6/3/39.

M. K. Hendrickson. Resilience in a concentrated and consolidated food system. *Journal of Environmental Studies and Sciences*, 5(3):418–431, Sept. 2015. ISSN 2190-6483, 2190-6491. doi: 10.1007/s13412-015-0292-2. URL http://link.springer.com/10.1007/s13412-015-0292-2.

J. E. Hobbs. Food supply chains during the COVID-19 pandemic. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 68(2):171–176, June 2020. ISSN 0008-3976, 1744-7976. doi: 10.1111/cjag.12237. URL https://onlinelibrary.wiley.com/doi/10.1111/cjag.12237.

J. E. Hobbs. Food supply chain resilience and the COVID-19 pandemic: What have we learned? *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 69(2):189–196, June 2021. ISSN 0008-3976, 1744-7976. doi: 10.1111/cjag.12279. URL https://onlinelibrary.wiley.com/doi/10.1111/cjag.12279.

IMPLAN. Updated RSC - Calculations, 2022.

Y. Liu and A. N. Rabinowitz. The impact of the COVID-19 pandemic on retail dairy prices. *Agribusiness*, 37(1):108–121, Jan. 2021. ISSN 0742-4477, 1520-6297. doi: 10.1002/agr.21687. URL https://onlinelibrary.wiley.com/doi/10.1002/agr.21687.

V. M. Merlino, M. Renna, J. Nery, A. Muresu, A. Ricci, A. Maggiolino, G. Celano, B. De Ruggieri, and M. Tarantola. Are Local Dairy Products Better? Using Principal Component Analysis to Investigate Consumers' Perception towards Quality, Sustainability, and Market Availability. *Animals*, 12(11):1421, May 2022. ISSN 2076-2615. doi: 10.3390/ani12111421. URL https://www.mdpi.com/2076-2615/12/11/1421.

A. Okrent and J. Alston. The Demand for Disaggregated Food- Away-From-Home and Food-at-Home Products in the United States. Economic Research Report 139, United States Department of Agriculture Economic Research Service, Aug. 2012.

A. J. Reed and J. W. Levedahl. Food Stamps and the Market Demand for Food. *American Journal of Agricultural Economics*, 92(5):1392–1400, Oct. 2010. ISSN 0002-9092, 1467-8276. doi: 10.1093/ajae/aaq069. URL https://onlinelibrary.wiley.com/doi/10.1093/ajae/aaq069.

S. Rotz and E. D. G. Fraser. Resilience and the industrial food system: analyzing the impacts of agricultural industrialization on food system vulnerability. *Journal of Environmental Studies and Sciences*, 5(3):459–473, Sept. 2015. ISSN 2190-6483, 2190-6491. doi: 10.1007/s13412-015-0277-1. URL http://link.springer.com/10.1007/s13412-015-0277-1.

B. J. Ryan, V. Telford, M. Brickhouse, J. Acosta, C. Allen, S. Bhatia, J. Campbell, C. Crowe, J. Everrett, M. Fendt, R. Fink, K. Hatch, T. Hatch, A. Johnson, R. Jones, L. A. Kanitz, L. Knapp, K. Krey, G. Larson, J. McKone, A. Santa Cruz, P. A. Sandifer, and B. W. Brooks. Strengthening Food Systems Resilience Before, During and After Disasters and Other Crises. *Journal of Homeland Security and Emergency Management*, 21(1):71–97, Feb. 2024. ISSN 1547-7355. doi: 10.1515/jhsem-2022-0028. URL https://www.degruyter.com/document/doi/10.1515/jhsem-2022-0028/html.

USDA. USDA Agri-Food Supply Chain Assessment: Program and Policy Options for Strengthening Resilience. Technical report, United States Department of Agriculture, 2022.

Q. Wang, C.-q. Liu, Y.-f. Zhao, A. Kitsos, M. Cannella, S.-k. Wang, and L. Han. Impacts of the COVID-19 pandemic on the dairy industry: Lessons from China and the United States and policy implications. *Journal of Integrative Agriculture*, 19(12):2903–2915, Dec. 2020. ISSN 20953119. doi: 10.1016/S2095-3119(20)63443-8. URL https://linkinghub.elsevier.com/retrieve/pii/S2095311920634438.

A. Weersink, M. Von Massow, N. Bannon, J. Ifft, J. Maples, K. McEwan, M. G. McKendree, C. Nicholson, A. Novakovic, A. Rangarajan, T. Richards, B. Rickard, J. Rude, M. Schipanski,

G. Schnitkey, L. Schulz, D. Schuurman, K. Schwartzkopf-Genswein, M. Stephenson, J. Thompson, and K. Wood. COVID-19 and the agri-food system in the United States and Canada. *Agricultural Systems*, 188:103039, Mar. 2021. ISSN 0308521X. doi: 10.1016/j.agsy.2020.103039. URL https://linkinghub.elsevier.com/retrieve/pii/S0308521X20309008.

C. A. Wolf, A. M. Novakovic, M. W. Stephenson, C. A. Wolf, A. M. Novakovic, and M. W. Stephenson. COVID-19 and the U.S. Dairy Supply Chain. 2021. doi: 10.22004/AG.ECON.311037. URL https://ageconsearch.umn.edu/record/311037. Publisher: [object Object].

W. Zhang and J. Alston. The Demand for Inputs and Technical Change in the U.S. Dairy Manufacturing Industry. *Agricultural and Resource Economics Review*, 47(3):533–567, Dec. 2018.

A Appendix

Parameters

Table 6: Description of Parameters - Fluid Milk

Local	Non-Local	Description	Source
fl_1	nfl_1	Proportion of milk sold within region to consumers	IMPLAN (2022)
fl_2	nfl_2	Proportion of milk sold outside of region to consumers	IMPLAN (2022)
fl_3	nfl_3	Proportion of milk sold within region to foodservice	IMPLAN (2022)
fl_4	nfl_4	Proportion of milk sold outside of region to foodservice	IMPLAN (2022)
$K_{1,l}^{fluid}$	$K_{1,nl}^{fluid}$	Cost share of input 1	Zhang and Alston (2018)
$K_{2,l}^{fluid}$	$K_{2,nl}^{fluid}$	Cost share of input 2	Zhang and Alston (2018)
$\epsilon_{1,l}^{fluid}$	$\epsilon_{1,nl}^{fluid}$	Supply elasticity for input 1	Zhang and Alston (2018)
$\epsilon_{2,l}^{fluid}$	$\epsilon_{2,nl}^{fluid}$	Supply elasticity for input 2	Zhang and Alston (2018)
η_{lc}^{fluid}	η_{nlc}^{fluid}	Price elasticity of milk at the consumer level	Davis et al. (2010)
$\gamma_{lc,nlc}^{fluid}$	$\gamma_{nlc,lc}^{fluid}$	Cross price elasticity for cross-regional milk at the consumer level	Donnelly et al. (2004)*
$\phi_{lc,FAH}^{fluid}$	$\phi_{nlc,FAH}^{fluid}$	Consumption elasticity of milk with respect to food expenditures	Okrent and Alston (2012)
$\phi_{lc,SNAP}^{fluid}$	$\phi_{nlc,SNAP}^{fluid}$	Consumption elasticity of milk with respect to SNAP expenditures	Reed and Levedahl (2010)
η_{lr}^{fluid}	η_{nlr}^{fluid}	Price elasticity of milk at the food service level	(Davis et al., 2010)*
$\gamma_{lr,nlr}^{fluid}$	$\gamma_{nlr,lr}^{fluid}$	Cross price elasticity for cross-regional milk at the foodservice level	Donnelly et al. (2004)*
$\phi_{lr,FAFH}^{fluid}$	$\phi_{nlr,FAFH}^{fluid}$	Foodservice price elasticity of milk with respect to FAFH	Okrent and Alston (2012)
$\gamma_{l,cheese}^{fluid}$	$\gamma_{nl,cheese}^{fluid}$	Substitution elasticity between milk and cheese	(Davis et al., 2010)*
$\gamma_{l,butter}^{fluid}$	$\gamma_{nl,butter}^{fluid}$	Substitution elasticity between milk and butter	(Davis et al., 2010)*

Elasticities

Table 7: Demand Elasticities - Fluid Milk

Elasticity	California	Upper Midwest	United States
η_c^{fluid}	-1.595	-1.696	-1.65
η_r^{fluid}	-1.435	-1.526	-1.485
$\gamma_{lc,nlc}^{fluid}$	2	2.5	5
$\gamma_{nlc,lc}^{fluid}$	10	10	10
$\gamma_{lr,nlr}^{fluid}$	4	4	4
$\gamma_{nlr,lr}^{fluid}$	10	10	10
$\phi_{c,expenditure}^{fluid}$	-	-	0.090
$\phi_{c,SNAP}^{fluid}$	-	-	0.020
$\phi_{r,FAFH}^{fluid}$	-	-	0.065

Table 8: Supply Elasticities

Elasticity	California	Upper Midwest	United States
ϵ_{feed}	-0.669	-1.204	-1.049
ϵ_{blend}	0.231	0.520	0.365
$\epsilon_{class\ I}^{fluid}$	-	-	-0.099
ϵ_{labor}^{fluid}	-	-	-0.311
$\epsilon_{class\ IV}^{butter}$	-	-	-0.090
$\epsilon_{labor}^{butter}$	-	-	-0.722
$\epsilon_{class\ III}^{cheese}$	-	-	-0.104
$\epsilon_{labor}^{cheese}$	-	-	-0.696

Full Model Matrix

$$\Gamma \times \Delta = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & fl_1 & fl_2 & fl_3 & fl_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & nfl_1 & nfl_2 & nfl_3 & nfl_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -K_{1,l}^{fluid} & 0 & -K_{2,l}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{1,nl}^{fluid} & 0 & -K_{2,nl}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -K_{1,l}^{fluid}\sigma_1 1 & 0 & -K_{2,l}^{fluid}\sigma_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{1,nl}^{fluid}\sigma_{11} & 0 & -K_{2,nl}^{fluid}\sigma_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -K_{1,l}^{fluid}\sigma_2 1 & 0 & -K_{2,l}^{fluid}\sigma_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{1,nl}^{fluid}\sigma_{21} & 0 & -K_{2,nl}^{fluid}\sigma_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -epsilon_{1,l}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -epsilon_{1,nl}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -epsilon_{2,l}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -epsilon_{2,nl}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\eta_{lc}^{fluid} & -\gamma_{lc,nlc}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -\phi_{lc,FAH}^{fluid} & 0 & -\phi_{lc,SNAP}^{fluid} & 0 & 0 & 0 & -\gamma_{lc,cheese}^{fluid} & 0 & -\gamma_{lc,butter}^{fluid} & 0 \\
0 & 0 & -\gamma_{nlc,lc}^{fluid} & -\eta_{nlc}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -\phi_{nlc,FAH}^{fluid} & 0 & -\phi_{nlc,SNAP}^{fluid} & 0 & 0 & 0 & -\gamma_{nlc,cheese}^{fluid} & 0 & -\gamma_{nlc,butter}^{fluid} \\
0 & 0 & -\eta_{lr}^{fluid} & -\gamma_{lr,nlr}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -\phi_{lr,FAFH}^{fluid} & 0 & -\gamma_{lr,cheese}^{fluid} & 0 & -\gamma_{lr,butter}^{fluid} & 0 \\
0 & 0 & -\gamma_{nlr,lr}^{fluid} & -\eta_{nlr}^{fluid} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -\phi_{lr,FAFH}^{fluid} & 0 & -\gamma_{lr,cheese}^{fluid} & 0 & -\gamma_{lr,butter}^{fluid} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix} \times \begin{bmatrix}
E(Q_{lp}^{fluid}) \\
E(Q_{nlp}^{fluid}) \\
E(P_{lp}^{fluid,D}) \\
E(P_{nlp}^{fluid,D}) \\
E(P_{lp}^{fluid,S}) \\
E(P_{nlp}^{fluid,S}) \\
E(Q_{lp}^{class\ I}) \\
E(Q_{nlp}^{class\ I}) \\
E(Q_{lp}^{labor}) \\
E(Q_{nlp}^{labor}) \\
E(P_{lp}^{class\ I,D}) \\
E(P_{nlp}^{class\ I,D}) \\
E(P_{lp}^{labor,D}) \\
E(P_{nlp}^{labor,D}) \\
E(P_{lp}^{class\ I,S}) \\
E(P_{nlp}^{class\ I,S}) \\
E(P_{lp}^{labor,S}) \\
E(P_{nlp}^{labor,S}) \\
E(Q_{lc}^{fluid}) \\
E(Q_{nlc}^{fluid}) \\
E(Q_{lr}^{fluid}) \\
E(Q_{nlr}^{fluid}) \\
E(X_{lc}^{FAH}) \\
E(X_{nlc}^{FAH}) \\
E(X_{lc}^{SNAP}) \\
E(X_{nlc}^{SNAP}) \\
E(X_{lc}^{FAFH}) \\
E(X_{nlc}^{FAFH}) \\
E(P_{lp}^{cheese,D}) \\
E(P_{nlp}^{cheese,D}) \\
E(P_{lp}^{butter,D}) \\
E(P_{nlp}^{butter,D})
\end{bmatrix} \tag{19}$$

Additional Commodity Results

Table 9: CA vs. UM Resilience Comparison - Butter

Variable	Regional CA	Regional UM	National CA	National UM	Dual CA	Dual UM
Q_{lp}^{butter}	-0.006	-0.017	-0.158	-0.018	-0.173	-0.044
Q_{nlp}^{butter}	-0.005	-0.011	-0.102	-0.005	-0.114	-0.024
$P_{lp}^{butter,D}$	0.028	0.060	0.699	0.064	0.763	0.159
$P_{nlp}^{butter,D}$	0.019	0.046	0.407	0.020	0.452	0.095
$P_{lp}^{butter,S}$	0.028	0.060	0.699	0.064	0.763	0.159
$P_{nlp}^{butter,S}$	0.019	0.046	0.407	0.020	0.452	0.095
$Q_{lp}^{class\ IV}$	-0.006	-0.017	-0.158	-0.018	-0.173	-0.044
$Q_{nlp}^{class\ IV}$	-0.005	-0.011	-0.102	-0.005	-0.114	-0.024
$P_{lp}^{class\ IV}$	0.079	0.169	1.952	0.179	2.131	0.443
$P_{nlp}^{class\ IV}$	0.054	0.127	1.138	0.055	1.263	0.265
Q_{lc}^{butter}	0.032	0.106	-0.620	-0.063	-0.585	0.107
Q_{nlc}^{butter}	-0.015	-0.124	0.255	0.107	0.235	-0.092
Q_{lr}^{butter}	-0.113	-0.035	0.644	-0.007	0.483	-0.060
Q_{nlr}^{butter}	-0.002	-0.009	-0.212	-0.218	-0.219	-0.237

Table 10: CA vs. UM Resilience Comparison - Cheese

Variable	Regional CA	Regional UM	National CA	National UM	Dual CA	Dual UM
Q_{lp}^{cheese}	-0.026	0.100	-0.115	0.061	-0.160	0.219
Q_{nlp}^{cheese}	-0.008	-0.016	0.042	-0.008	0.030	-0.035
$P_{lp}^{cheese,D}$	0.096	-0.300	0.421	-0.184	0.586	-0.658
$P_{nlp}^{cheese,D}$	0.026	0.053	-0.138	0.027	-0.098	0.115
$P_{lp}^{cheese,S}$	0.096	-0.300	0.421	-0.184	0.586	-0.658
$P_{nlp}^{cheese,S}$	0.026	0.053	-0.138	0.027	-0.098	0.115
$Q_{lp}^{class\ III}$	-0.026	0.100	-0.115	0.061	-0.160	0.219
$Q_{nlp}^{class\ III}$	-0.008	-0.016	0.042	-0.008	0.030	-0.035
$P_{lp}^{class\ III}$	0.281	-0.875	1.227	-0.537	1.710	-1.919
$P_{nlp}^{class\ III}$	0.076	0.156	-0.404	0.079	-0.286	0.335
Q_{lc}^{cheese}	-0.050	0.710	-0.829	0.360	-0.933	1.482
Q_{nlc}^{cheese}	0.060	-0.646	1.068	-0.242	1.192	-1.266
Q_{lr}^{cheese}	-0.170	0.492	-1.096	0.369	-1.398	1.149
Q_{nlr}^{cheese}	0.053	-0.355	0.307	-0.461	0.404	-1.026