



OPEN ACCESS

EDITED BY

Jabir Arif,
Sidi Mohamed Ben Abdellah University,
Morocco

REVIEWED BY

Bing He,
Jiangsu Ocean University, China
Urmisha Das,
Lincoln University College, Malaysia
Fatima Zahra Benbrahim,
Ibn Tofail University, Morocco

*CORRESPONDENCE

Megan Konar
✉ mkonar@illinois.edu

RECEIVED 07 July 2025

REVISED 14 November 2025

ACCEPTED 15 December 2025

PUBLISHED 16 January 2026

CITATION

Zhang R, Arnav A, Karakoc DB and Konar M
(2026) Compound shocks to agri-food supply
chain transport and trade in the United States.
Front. Sustain. Food Syst. 9:1661492.
doi: 10.3389/fsufs.2025.1661492

COPYRIGHT

© 2026 Zhang, Arnav, Karakoc and Konar. This
is an open-access article distributed under the
terms of the [Creative Commons Attribution
License \(CC BY\)](#). The use, distribution or
reproduction in other forums is permitted,
provided the original author(s) and the
copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic practice.
No use, distribution or reproduction is
permitted which does not comply with these
terms.

Compound shocks to agri-food supply chain transport and trade in the United States

Rui Zhang¹, Arushi Arnav¹, Deniz Berfin Karakoc² and
Megan Konar^{1*}

¹Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States, ²School of Computing and Augmented Intelligence, Arizona State University, Tempe, AZ, United States

Agri-food supply chains are important for national food security and economic stability but remain highly vulnerable to multiple natural and socioeconomic shocks. This study examines how such compound shocks affected transport and trade of the US agri-food supply chain from 2018 to 2022. Using the Freight Analysis Framework database, we quantify temporal and spatial changes in domestic, import, and export agri-food flows, and apply a weighted node-degree network analysis to assess regional resilience during this time period, which included the US-China trade war, COVID-19 pandemic, and severe flood and drought events. Our results identify the locations and commodities that were most impacted and resilient to shocks. For example, Midwestern agricultural hubs were severely affected during floods, while urban logistics centers exhibited prolonged recovery following the pandemic. Our analysis highlights regional differences in network adaptability and identifies key commodities driving these dynamics. These findings provide insights for strengthening transport infrastructure, diversifying supply routes, and improving systemic resilience of national food supply chains under future shocks.

KEYWORDS

shocks, agri-food, supply chain, transportation, drought, flood, trade war, pandemic

1 Introduction

Agri-food systems are increasingly exposed to environmental and socioeconomic shocks that threaten their ability to ensure safe, sufficient, and stable food supplies. These shocks, such as droughts, floods, pandemics, and trade disruptions, can spread far beyond their origin through global supply chains. As Davis et al. emphasize, most research has focused on production shocks, while downstream stages like transportation, processing and trade remain understudied despite their crucial role (Davis et al., 2021). All shocks can propagate globally via economic, political, and infrastructure pathways, triggering food shortages and price spikes in regions far removed from the initial disruption. Understanding how systemic shocks ripple through such national systems is key to improving supply chain resilience at both domestic and global levels.

Global vulnerability to shocks is particularly significant for countries that are major hubs in international food trade. As one of the world's largest agricultural producers and exporters, the United States plays a pivotal role in the global food trade network that not only feeds the domestic population, but also supplies many countries with essential agri-food commodities (Ercsey-Ravasz et al., 2012; Wang and Dai, 2021; Zhang et al., 2025). This central position means that disruptions to the US agri-food system

can have far-reaching effects on global markets. As part of this global network, the United States is a major exporter of bulk agricultural commodities while simultaneously importing processed food and perishable products such as fruits and vegetables, reflecting a trade structure that links domestic logistics to international markets and concentrates flows through key national hubs (Karakoc et al., 2023). Within this global context, the US agri-food supply chain is sustained by a highly interconnected multimodal transport network that connects production regions, processing centers, and consumption areas via highways, railways, and waterways, sustaining both domestic distribution and international exchange (Karakoc and Konar, 2025).

Between 2018 and 2022, the US agri-food system experienced a series of overlapping shocks, including the US-China trade conflict, major flooding and droughts, and the COVID-19 pandemic, which disrupted production, trade, and logistics across multiple nodes of the supply chain. Retaliatory tariffs during the trade war led to an estimated \$27 billion reduction in agricultural exports (Morgan et al., 2022). Flooding in 2019 left over 11 million acres unplanted across Iowa, Illinois, and Missouri, resulting in billions in crop losses (English et al., 2022; National Weather Service (NWS), 2019). The pandemic triggered abrupt shifts in demand and widespread labor shortages, causing mismatches between supply and retail (Hobbs, 2021b; Aday and Aday, 2020; Hobbs, 2021a).

To address this challenge, our study provides a quantitative, network-based analysis of agri-food flows across the United States using Freight Analysis Framework (FAF) data. We focus on the temporal trajectories and spatial reconfiguration of flows across regions and commodities. The analysis is guided by three key research questions: (1) How did national-level food flows change from 2018 to 2022? (2) What spatial locations experienced the largest changes in the US agri-food flows? (3) How did the network structure of different locations respond to shocks?

2 Literature review

Existing literature has identified various vulnerabilities in food supply chains, ranging from farm-level production disruptions to logistical challenges in distribution and retail (Crimmins and Kosmal, 2023). Modern food supply chains, particularly in developed economies like the United States, typically rely on centralized facilities and precise delivery schedules to maximize efficiency. While these highly tuned systems function effectively under normal conditions, their limited redundancy means that shocks can quickly cause disruptions throughout the entire network (Hobbs, 2021b).

The COVID-19 pandemic, as an unprecedented global shock, simultaneously impacted multiple sectors within the food supply chain. In its early stages, rapid shifts in consumer demand from restaurants to grocery stores necessitated a swift realignment of supply channels (Hobbs, 2021a). Domestically, the food distribution network faced mismatches where producers experienced surpluses of perishable goods while store shelves went empty (Hobbs, 2021b). Environmental shocks have posed similar challenges to the supply chain system. In spring 2019, severe flooding across eastern Iowa, northwest Illinois, and northeast

Missouri disrupted agricultural production of major crops, leading to substantial financial losses. With approximately 11.4 million acres of corn left unplanted, foregone gross revenue from crop sales alone likely exceeded six billion dollars (English et al., 2022; National Weather Service (NWS), 2019).

These shocks have prompted a growing body of research examining their impacts on the US agri-food supply chain. For instance, Morgan et al. (2022) conducted economic analyses showing that retaliatory tariffs from the US-China trade conflict resulted in a \$27 billion reduction in US agricultural exports from mid-2018 to late 2019. English et al. (2022) documented widespread Midwest flooding and unprecedented levels of prevented planting affecting millions of acres. Similarly, Yao et al. (2023) applied spatial analysis to assess the combined effects of COVID-19 and climate change on global agriculture and food supply systems. Broader reviews, such as that by Aday and Aday (2020), summarized pandemic-induced challenges including labor shortages, shifts in demand, and increased financial pressures across agricultural supply chains.

In addition to these general analyses, several studies have focused on specific sectors within the food supply chain, providing more detailed insights into particular industries. Luckstead et al. (2021) explored labor market disruptions caused by logistics realignments, while Anderson et al. (2021) examined the effects of COVID-19 on US meat and poultry industries. Additionally, Hobbs (2021b) provided comprehensive assessments of North American food supply chain challenges during the pandemic.

Although prior research has substantially advanced understanding of disruptions to food supply chains, existing studies remain fragmented across sectors and scales. Most have examined production, trade, or logistics in isolation, providing limited insight into how disruptions collectively reshape the spatial and temporal structure of agri-food transport and trade within the United States. Few have quantified how regional connectivity and flow patterns respond to stress, leaving an incomplete picture of the supply chain system's adaptive capacity. Our study addresses these gaps by integrating a network-based, quantitative framework to evaluate changes in US agri-food transport and trade. By analyzing flow dynamics across regions and commodities, our work provides a comprehensive perspective on how the structure and connectivity of the agri-food transport system evolve under disruption and thus extends existing literature from sector-specific analyses toward a system-level understanding of supply chain resilience.

3 Methods

The US agri-food system relies on large-scale, multimodal transportation networks to move food from production regions to domestic and international markets. Before the COVID-19 pandemic, these systems operated under centralized, just-in-time logistics models focused on efficiency (Hobbs, 2021b). The pandemic, however, revealed systemic vulnerabilities in processing, labor, and distribution, leading to widespread mismatches between supply and demand (Aday and Aday, 2020; Hobbs, 2021a). These disruptions highlight the need for evaluations of how agri-food transport responds to shocks. In this study, we use empirical data and a network-based framework to quantify temporal and spatial

TABLE 1 List of food commodity groups included in this study.

| SCTG code | Food commodity |
|-----------|--|
| 01 | Live animal and fish |
| 02 | Cereal grains |
| 03 | Agricultural products (except for animal feed, cereal grains, and forage products) |
| 04 | Animal feed, eggs, honey, and other products of animal origin |
| 05 | Meat, poultry, fish, seafood, and their preparations |
| 06 | Milled grain products and preparations, and bakery products |
| 07 | Other prepared foodstuffs, fats, and oils |

changes in domestic, import, and export food flows during multiple recent disruptions.

3.1 Freight Analysis Framework database

The main data we use in this study is the annual agri-food flow at the Freight Analysis Framework scale from 2017 to 2022. The Freight Analysis Framework (FAF) data creates a comprehensive dataset of freight movement among states and major metropolitan areas through a partnership between the US Bureau of Transportation Statistics and the Federal Highway Administration (FAF, 2020).

FAF provides commodity-specific information classified according to the Standard Classification of Transported Goods (SCTG) (FAF, 2020). In this analysis, we focus on SCTG groups 1–7, collectively defined as agri-food commodities (Table 1). To capture the broad understanding of US food supply chains, we consider three types of agri-food flows: (i) domestically produced and consumed, (ii) imported, and (iii) exported commodities. For domestic flows, the origins and destinations of the food flow are both within the United States. For exports, we focus on the domestic origins of shipments for international markets, while for imports, we focus on the domestic destinations receiving foreign-produced products. We examine both the temporal and spatial changes in individual commodity networks and in aggregated food shipments from 2018 to 2022. While FAF datasets are available for the period 2017–2022, we focus our primary analysis on the years 2018–2022, which encompass the major compound shocks of interest, including the US–China trade war, COVID-19 pandemic, and extreme weather events. We retain 2017 as a reference year for selected baseline comparisons where appropriate.

3.2 Weighted node degree network analysis

Food supply chain complexity and diversity play a critical role in determining a region's resilience to shocks (Gomez et al., 2021; Doğan et al., 2023). We thus evaluate the resilience of each FAF region within the agri-food supply chain network by analyzing

its network structure complexity. Specifically, we calculate the weighted node degree of each FAF zone, following the approach proposed by Opsahl et al. (2010). Weighted node degree balances the importance of both the number of connections (degree) and the total amount of flow (node strength) for each FAF zone.

In a directed network $G = (V, E)$, let V be the set of nodes and E be the set of edges. Each node $i \in V$ represents a FAF region and each edge w_{ij} connecting node i to node j also captures the magnitude of directed agri-food flow between two FAF regions i and j . The *degree* of node i , denoted as k_i , is defined as the number of nodes to which i is directly connected:

$$k_i = \sum_{j=1}^N x_{ij}, \quad (1)$$

where N is the total number of nodes, and $x_{ij} = 1$ if node i is connected to node j , and 0 otherwise. In our study, nodes i and j are determined as connected when there is a non-zero agri-food flow between these two nodes.

To account for the magnitude of each food flow, we incorporate edge weights by defining the *node strength* s_i as:

$$s_i = \sum_{j=1}^N w_{ij}, \quad (2)$$

where $w_{ij} > 0$ is the weight of the edge between nodes i and j , representing the quantity of food flow. And N is the total number of nodes. Although node strength is often the preferred method in weighted networks due to its focus on flow volume (Barrat et al., 2004; Opsahl et al., 2008), it does not capture the number of links a node connects. Conversely, degree alone does not reflect the volume of flow passing through a node. Therefore, following Opsahl et al. (2010), we combine these two measures into a single metric:

$$C_D^{w\alpha}(i) = k_i^{(1-\alpha)} s_i^\alpha, \quad (3)$$

where α is a tuning parameter that determines the relative importance of the degree and strength.

The value of α can range between 0 and 1, providing a continuum between pure degree (when $\alpha = 0$) and pure node strength (when $\alpha = 1$). A lower α places greater emphasis on the number of connections, while a higher α places more emphasis on the weight of those connections. In this study, we choose $\alpha = 0.5$ with an equal balance between the degree and the strength. By doing so, regions that connect to many other regions with smaller flows and those that connect to fewer nodes with very large flows are treated more comparably. The weighted node degree $C_D^{w\alpha}$ offers a comprehensive understanding on each region's role within the domestic agri-food network. The change in this metric can signal shifts in a region's resilience under certain disruptions. Higher $C_D^{w\alpha}$ values suggest that the region maintains a diverse set of trading partners and routes or that it maintains a substantial volume of agri-food flows, showing its significance as a key supplier or recipient. By tracking how $C_D^{w\alpha}$ changes over time, particularly during and after pandemic disruptions, we can gain a clearer understanding of the role each FAF region plays in addressing supply chain challenges. All data processing, network construction, and metric calculations were conducted in Python 3.10.

4 Results and discussion

This section addresses the research questions in detail, analyzing the impacts of multiple shocks on US agri-food transportation and trade. Figure 1 provides an overview of the major shocks that occurred during the 2018–2022 study period, which collectively influenced the evolution of agri-food flows and network structure across the United States. The first of these events was the US–China trade war, which officially started on 15 June 2018, when the United States announced increased tariffs on Chinese goods, and ended on 15 January 2020 with the signing of the Phase One trade agreement between the two countries (Reuters, 2019; Office of the United States Trade Representative, 2020). Soon after, the Midwest experienced severe flooding from January to July 2019, disrupting large areas of farmland and transportation networks (National Centers for Environmental Information (NCEI), NOAA, 2020). Beginning in early 2020, the COVID-19 pandemic caused unprecedented disruptions to global food trade and logistics, lasting from March 2020 to May 2023 (World Health Organization, 2020, 2023). Although the pandemic persisted as a public health event through 2023, its disruptive effects on the US food supply chain had largely diminished by late 2021–2022, according to USDA analyses [U.S. Department of Agriculture, Economic Research Service (ERS), 2023]. During 2021–2022, widespread drought conditions affected more than 60 percent of the contiguous United States and resulted in substantial agricultural production losses (National Oceanic and Atmospheric Administration, 2023).

4.1 How did national-level food flows change during 2018–2022?

National-level changes in food flows from 2017 to 2022 are illustrated in Figure 2, considering three food flow types: domestic, import, and export. As shown in Figure 2a, the total domestic food flow remained relatively stable throughout the period. In 2019 and 2022, however, the total domestic food flow mass reached its lowest levels at approximately 3.093×10^{12} kg and

3.08×10^{12} kg, respectively. The 2019 decline is likely attributable to extreme flooding across the Midwest. According to the USDA, as of November 1, 2019, a record 19.4 million acres of farmland remained unplanted due to flood conditions (U.S. Department of Agriculture, Farm Service Agency (FSA), 2019), with additional losses caused by harvest delays and freeze damage (Randall, 2019). This decline was followed by a strong rebound in 2020 and a notable peak in 2021, suggesting a two-year recovery trajectory. 2021 recorded the highest domestic mass flux at about 3.23×10^{12} kg. This increase may reflect a combination of post-pandemic recovery dynamics, including the return of eating out expenditures, and adaptive logistics strategies within the food supply chain. During this period, distributors, logistics providers, and packaging facilities reconfigured supply channels, repackaged goods for retail markets, and addressed labor constraints, thereby enabling a notable resurgence in domestic food movement [U.S. Department of Agriculture, Economic Research Service (ERS), 2023]. In 2022, the total domestic mass flux decreased, largely due to widespread drought conditions. That year, drought affected about 63% of the contiguous United States and caused extensive agricultural stress and an estimated 22 billion dollars in losses (National Centers for Environmental Information (NCEI), 2023). The most severe impacts occurred in the Central and Western states, which include many of the nation's major agricultural production areas (National Oceanic and Atmospheric Administration, 2023). In contrast, the economic and logistical disruptions associated with COVID-19 had largely subsided as supply chains and markets adapted, indicating that drought effects were the primary driver of the 2021–2022 decline.

Export flow volumes followed a similar temporal pattern as Figure 2b suggested, with the lowest value occurring in 2019 at 2.17×10^{11} kg. Unlike domestic food flow, where cereal grains (SCTG 02) dominated, agricultural products (SCTG 03) accounted for the largest share of exports. Notably, SCTG 3 exports rose in 2018 despite the situation of the US–China trade war. While it was expected that export volumes would decline due to tariffs, actual volumes increased as producers redirected supply to alternative international buyers. However, based on our analysis of FAF volumes and export price trends, the total trade value for SCTG 3 declined in 2018, indicating that US agricultural

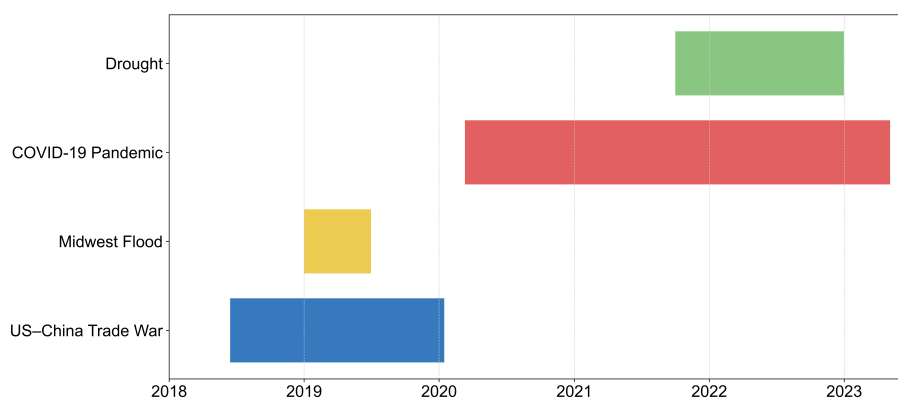
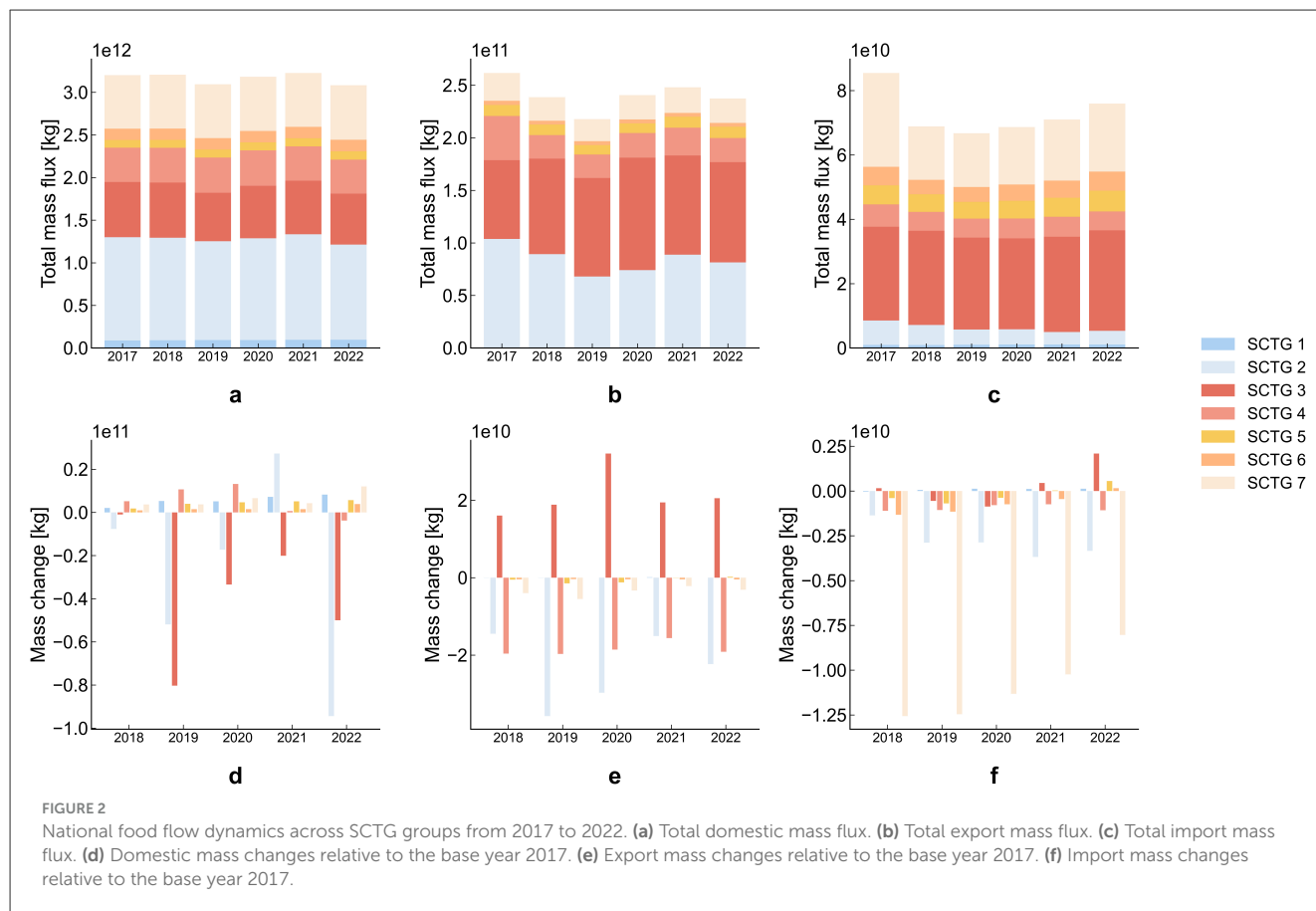


FIGURE 1
Timeline of major compound shocks affecting the US agri-food system.



product, particularly soybeans, were sold at lower prices to alternative buyers.

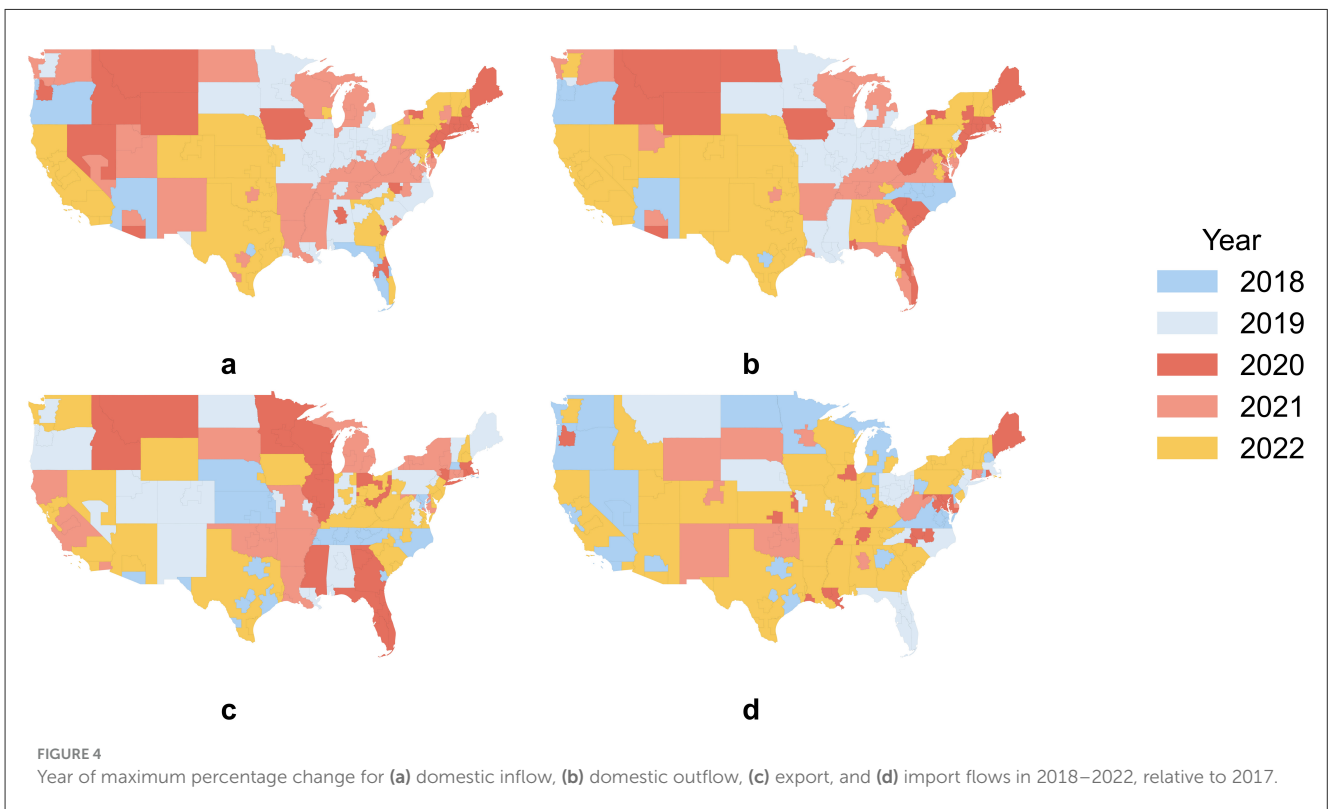
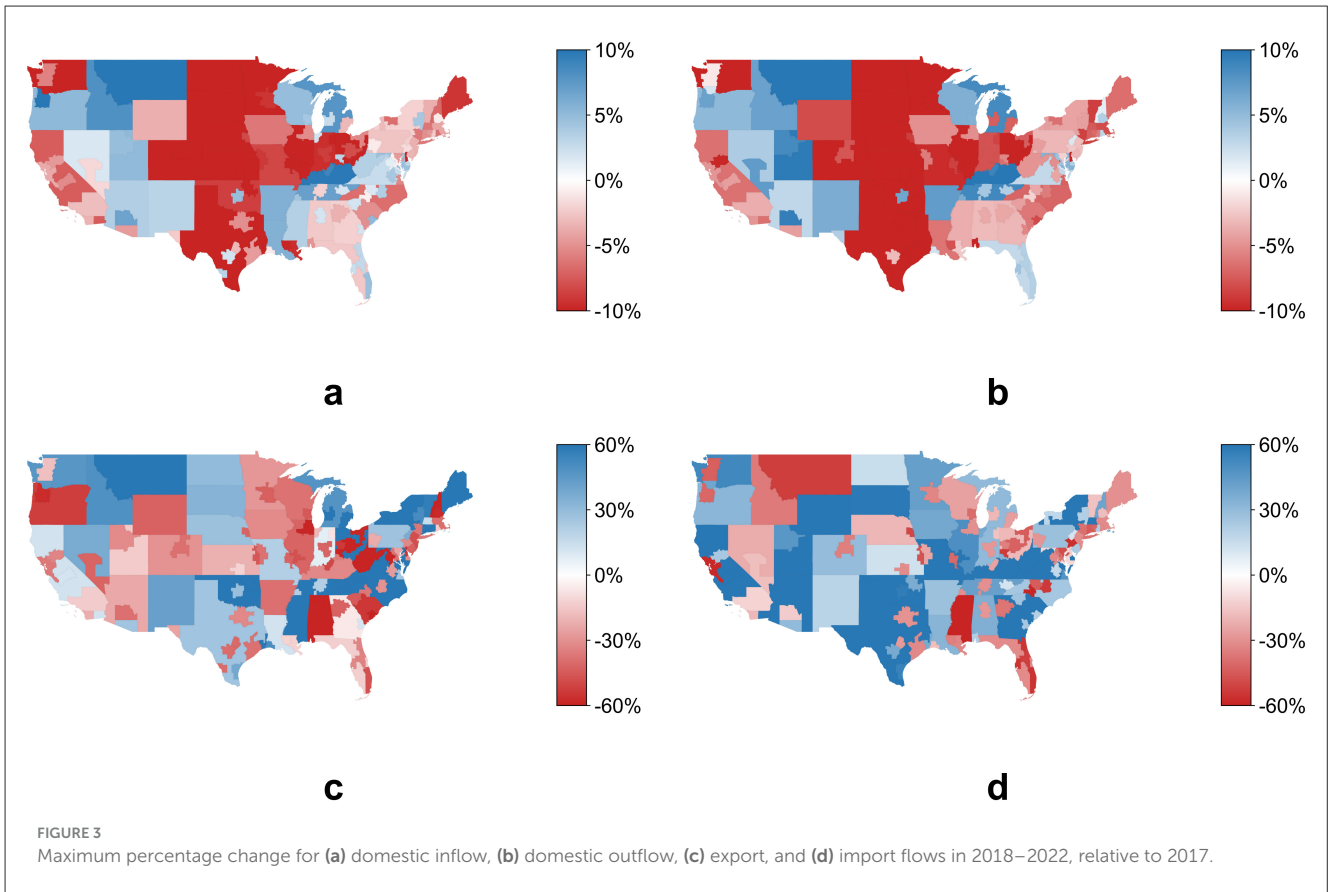
A distinct shift emerged in 2019 for SCTG 03: domestic flows declined sharply shown in Figure 2a, while exports and imports remained relatively stable (Figures 2b, c). The observed divergence in 2019 likely reflects the combined effects of production losses caused by the Midwest floods and the gradual easing of trade tensions toward the end of that year. As shown in Figure 1, discussion on tariff relaxations and renewed agricultural purchases between the United States and China began in late 2019, preceding the signing of the Phase One agreement in January 2020. Reports from USDA and USITC also indicate that soybean inventories accumulated during the record 2018 harvest were drawn down to meet external demand as global prices adjusted and trade conditions stabilized (Cowley, 2020; U.S. Department of Agriculture, Foreign Agricultural Service (FAS), 2020; U.S. International Trade Commission, 2019). Although other factors such as price movements and logistics recovery may also have played a role, the temporal overlap between policy relaxation and export stability suggests that these trade policy adjustments helped prevent further export declines during this period.

Meanwhile, Figure 2c shows that import food flow volumes declined steadily from 2017 to 2019, reaching a minimum of 6.69×10^{10} kg, followed by gradual recovery in subsequent years. The US–China trade war led to reciprocal tariffs, reduced bilateral agricultural trade, and widespread market uncertainty (Melton and Cooke, 2018; U.S. International Trade Commission, 2019).

In 2019, US agricultural imports from China fell by 28%, and the national agri-food trade balance shifted into deficit for the first time since 2007 (Melton and Cooke, 2018). From 2020 onward, import volumes steadily rebounded, aided by stronger consumer demand and improved global trade logistics. This steady growth also aligns with the implementation of the United States–Mexico–Canada Agreement (USMCA) in July 2020, which maintained tariff-free agricultural trade and simplified border procedures that likely supported the increase of imports in 2021–2022.

4.2 What spatial locations experienced the largest changes in agri-food flows?

Figures 2, 3 present spatial and temporal variations in food flows between 2018 and 2022 for all SCTG combined. Figure 2 shows the maximum annual percentage changes in food flows relative to 2017, with panels depicting (Figure 2a) domestic inflows—food shipped into each FAF zone, Figure 2b domestic outflows—food shipped out from each FAF zone, Figure 2c export flows—food shipped from FAF zones to international markets, and Figure 2d import flows—food received from abroad by FAF zones. Figure 4 complements this by indicating the specific years in which these maximum changes occurred for Figure 4a domestic inflows, Figure 4b domestic outflows, Figure 4c exports,



and Figure 4d imports. For detailed results by commodity group, see Supplementary material.

For domestic flows in 2018, most maximum percentage changes were positive, particularly in states such as South Dakota and Illinois. Illinois, as a major soybean producer in the US, notably increased its food flow volume in 2018. That year, Illinois soybean production was the highest of any state, reaching nearly 700 million bushels. Yields also rose significantly, increasing by over 10% from the previous year (Newton, 2019).

In 2019, Iowa experienced one of the largest decreases in domestic outflows. This could possibly due to the widespread spring flooding across the Midwest, driven by heavy rainfall and rapid snowmelt. Floodwaters delayed planting, damaged infrastructure, and disrupted farm-to-market transportation across Iowa and surrounding states. These events contributed to a national record of nearly 20 million unplanted acres [U.S. Department of Agriculture, Farm Service Agency (FSA), 2019; Johnson and Monke, 2019], with domestic food trade performance visibly impacted in affected regions (Figure 3b). Beyond farm-level losses, transportation are also disrupted due to the flood and thus, reducing food supply from Iowa and its neighboring states to other states.

In 2020, states such as Montana and Idaho experienced decreases in domestic food flows. In Montana, the cattle industry was significantly affected as meatpacking plants nationwide temporarily shut down due to COVID-19 outbreaks, reducing slaughter capacity and slowing downstream movement (Hettinger, 2020). Idaho's potato industry also faced major disruption following a sharp drop in demand from the food service sector. Since approximately half of US potato production serves restaurants, Idaho farmers were left with about 1.5 billion pounds of surplus potatoes during spring 2020. With reduced processing capacity, potato usage in the state dropped by 26.5% in April 2020 compared to the previous year (Karan et al., 2023; Hobbs, 2021b). Wyoming's sheep ranching sector also faced disruptions, with labor shortages and logistic delays hampering processing and delivery (Kayne Pyatt, 2020).

In 2021, domestic outflows declined sharply in parts of the Central and Northern Plains. Iowa, Nebraska, and South Dakota all showed significant reductions in outflow volumes, aligning with the 2021 drought. By late summer, over 75% of Iowa and neighboring states were under moderate to severe drought (National Centers for Environmental Information, 2021), which likely contributed to lower crop yields and reduced outbound food movement. These stressors were further compounded by soil moisture deficits and degraded pasture conditions, particularly in Nebraska and South Dakota (USDA National Agricultural Statistics Service, 2021). Figure 3b confirms the spatial correspondence between drought exposure and domestic outflow contraction. Meanwhile, the largest percentage increases in 2021 were observed in parts of the Great Lakes region, including Wisconsin, Michigan, Indiana, and Ohio, suggesting a potential recovery following the pandemic.

In 2022, the central United States, including Nebraska, Kansas, Oklahoma, Colorado, and Texas, saw significant declines in both domestic inflows and outflows. These changes align with widespread drought conditions across the region. In Nebraska,

97% of the land experienced drought at its peak, with 41% of pasture rated poor or very poor (Nebraska Farm Bureau, 2022). Colorado experienced similarly severe drought, with 92% of its land affected and over half of both topsoil and subsoil rated as moisture-deficient. As a result, winter wheat and pasture conditions worsened considerably (U.S. Department of Agriculture, National Agricultural Statistics Service, 2022).

Regarding exports, the Midwest did not show maximum percentage changes in 2018, likely due to shifts in trade partners caused by the US–China trade war. In 2019, Oregon, Utah, and Colorado experienced decreases in exports. In Oregon, international trade tensions, particularly from the US–China trade war, reduced demand for several export commodities. For example, Chinese tariffs significantly impacted Oregon's agricultural exports, such as cherries. In 2018, China increased tariffs on US cherries from 10% to 40%, severely affecting exports from the Northwest region (Wojtanik, 2019). Utah, known for producing alfalfa hay, beef, and dairy, also saw substantial declines. During the peak of the trade war, Utah's agricultural exports to China fell by around 15%. Specifically, alfalfa hay exports dropped by over 20%, and beef and dairy exports declined by about 15%–20% due to tariffs and shifts in China's purchasing to other countries such as Brazil and European nations (Farmonaut, 2020).

Agriculture is vital to Colorado's exports, including beef, dairy, wheat, corn, and processed foods. When the US imposed steel and aluminum tariffs, major trading partners like Canada, Mexico, China, and the EU responded with retaliatory tariffs on US agricultural products. Consequently, Colorado's food exports declined sharply. By mid-2019, Colorado's food exports were down 17% year-over-year, primarily due to uncertainties in trade policy. This uncertainty discouraged overseas buyers from committing to long term contracts. Key markets such as Canada, Mexico, China, and Japan which are all significant importers of Colorado products, were particularly affected (Leeds School of Business, University of Colorado Boulder, 2019). For instance, Mexico, Colorado's export market, placed retaliatory tariffs on US's pork, dairy, apples, and potatoes in mid-2018, directly impacting Colorado hog producers (Chappell, 2018). Canada similarly imposed tariffs of 10%–20% on many US food and beverage products. Colorado's exports of non-alcoholic beverages to Canada declined about 40%, dropping from 58 million to 36 million dollar (Colorado General Assembly, 2019).

In 2020, the Midwest experienced significant decreases in exports, primarily due to pandemic related disruptions. For example, Minnesota's exports fell to approximately 20 billion dollars, marking a 10% reduction from 2019. State officials attributed this decline directly to COVID-19, highlighting widespread delays and market uncertainties (Toth, 2021). Similarly, most states across the US experienced reduced exports in 2020, with Midwestern states notably affected due to the global economic slowdown (Numbers, 2021).

For imports, in 2022, the United States experienced a significant increase in agricultural imports, particularly across large areas in the central and southeastern regions, as well as parts of the Northeast and Southwest. US agricultural imports reached approximately 200 billion dollar, an increase of 14.7% compared to 2021. This growth was mainly driven by horticultural products such as fruits, vegetables, wines, and nuts. The rise in imports reflects

higher consumer demand for fresh and varied foods available throughout the year, along with favorable exchange rates that made imported goods more competitive (Nigh, 2023; Kaufman, 2025). Specifically, imports of fresh vegetables and fruits saw notable growth, with vegetable imports alone increasing by 7%, reaching around 10.7 billion dollar (Specialty Crop Grower, 2023).

The southwestern United States, particularly states such as Texas, Arizona, New Mexico, and parts of southern California that border Mexico, is a key region for agricultural imports, especially from Mexico. Due to their geographic proximity, these states receive significant amounts of Mexican agricultural products through land transportation. In 2022, US imports of fresh and processed fruits, vegetables, and nuts from Mexico were estimated at approximately 18.7 billion dollars (Paul Schattenberg, 2023). Additionally, policies such as the North American Free Trade Agreement (NAFTA) and its successor, the United States-Mexico-Canada Agreement (USMCA), have facilitated tariff free agricultural trade between the US and Mexico, significantly boosting these imports into the southwestern states (Fresh Fruit Portal, 2025).

Other than higher consumer demand and favorable trading conditions and policies, a reduction in local agricultural supply due to extreme weather events further increases imports in 2022. For example, Florida's Valencia orange production fell to a historic low of 434,000 tons due to damage caused by Hurricane Ian. Because 96% of Florida's Valencia oranges are processed into juice, domestic orange juice production dropped to its lowest level in at least 50 years. Consequently, US orange juice imports increased by 30% in the 2022–23 season, reaching 574 million gallons (Citrus Industry, 2023).

4.3 How did the network structure of different locations respond to shocks?

To quantify the resilience of the current US food supply system under various shocks, we utilize weighted node degree to capture both reductions in connectivity and mass flux, as well as their rebound. By comparing temporal changes from 2018 to 2022 (Figures 5a–e), we trace how regional connectivity responded over time to different shocks. As shown in Figure 5, the x-axis represents changes in the weighted inflow node degree for each Freight Analysis Framework (FAF) region, while the y-axis represents changes in the weighted outflow node degree. Each quadrant corresponds to a distinct pattern: the first quadrant indicates increases in both inflows and outflows, the second quadrant shows increased outflows but decreased inflows, the third quadrant represents decreases in both, and the fourth quadrant shows increased inflows but decreased outflows. Figures 5a–e illustrate between-year changes from 2017 to 2022.

The COVID-19 pandemic impacted different regions and commodities in the US supply chain variably, in both the magnitude of disruption and the speed of recovery, as shown in Figures 5d, e. Between 2020 and 2021, some regions like Iowa, Rest of KS, Rest of IL, shifted from the third quadrant (reduced inflow and outflow) to the first or

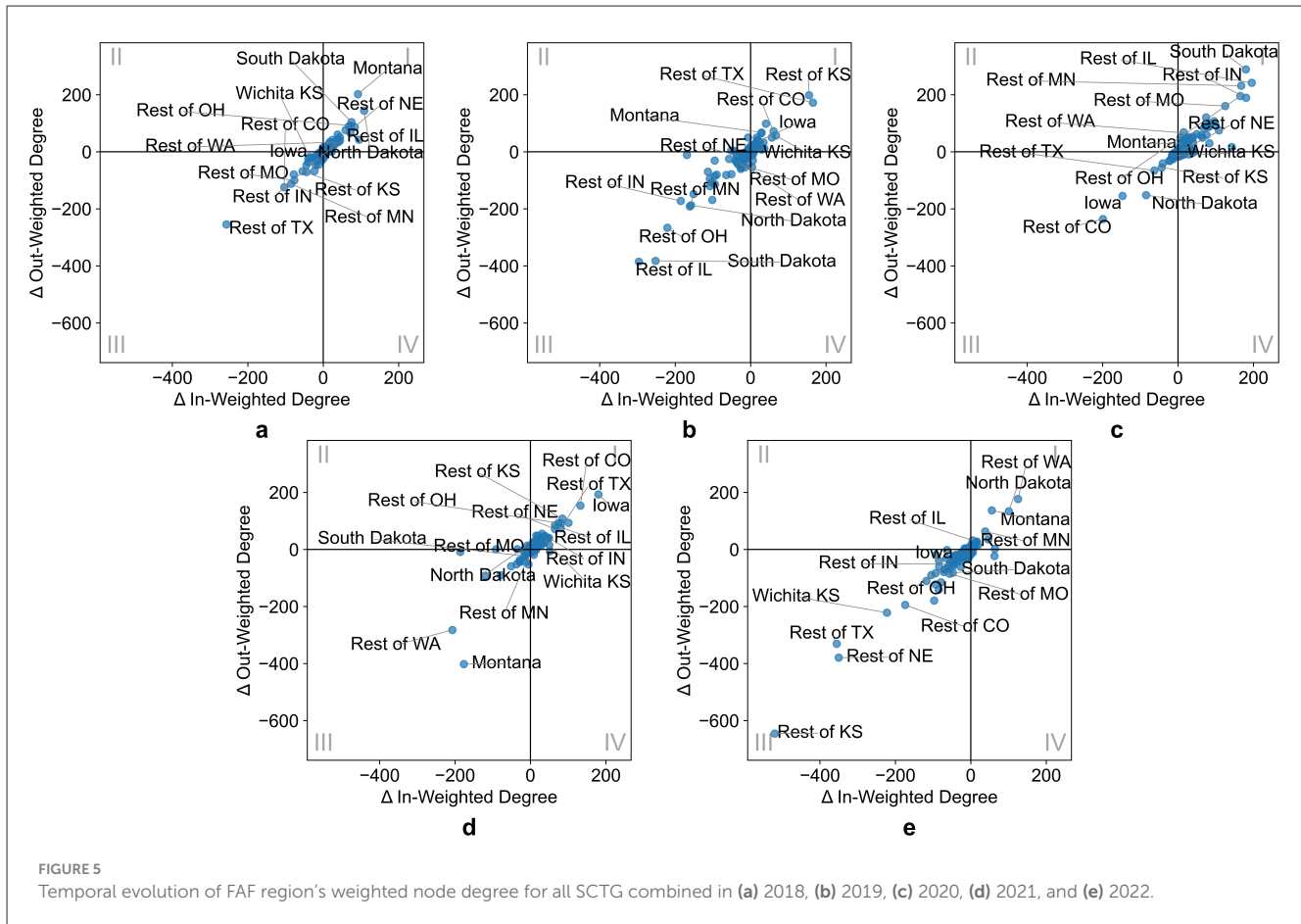
second quadrant, reflecting early stages of structural recovery in food logistics. This rebound suggests improvements in both movement volume and network connectedness. In contrast, several urban nodes such as Portland or Rest of WA remained near the origin or shifted minimally, indicating a slower recovery in more urbanized or import dependent systems. These differences could be linked to regional production structures, commodity specific characteristics, and disruption propagation pathways.

For example, Iowa, a major cereal grain producer (SCTG 02), was notably impacted due to reduced biofuel demand when travel dropped during lockdowns. However, demand rebounded relatively quickly once travel resumed (Hart et al., 2020), restoring flows to pre-pandemic levels in the next year. Similarly, Rest of CO and Rest of NE also moved upward and rightward, indicating restored export movement and increased inflows. These cases reflect how resilience varied not only by region but also by network function and commodity type.

Extreme weather events such as droughts and floods had strong but different impacts on agricultural production and transportation. These disruptions were often more severe but did not last as long as those caused by trade conflicts or the COVID-19 pandemic. For instance, the severe drought conditions across the United States in 2022 substantially disrupted both agricultural output and transportation logistics, notably pushing more nodes into the third quadrant in Figure 5e, signifying simultaneous declines in inflows and outflows. Similarly, the extensive flooding along critical waterways like the Mississippi River in 2019 severely disrupted grain shipping routes, affecting inflows and outflows at essential nodes, including Illinois and Ohio. Nevertheless, these disruptions showed quicker recovery trajectories, as evidenced by the notable rebound of Midwestern agricultural regions in 2020, even amidst the ongoing pandemic.

In contrast to rural agricultural regions, urban logistics hubs experienced slow recovery following disruptions. Cities such as New York, Boston, and Los Angeles faced prolonged impacts from pandemic-induced labor shortages and shifts in processed food demand. For example, meat, poultry, fish, and seafood commodities (SCTG 05) continued to experience substantial negative impacts in New York through 2022, as shown in Supplementary Figure 16. Similarly, Los Angeles saw persistent declines in milled grain products (SCTG 06) lasting until 2021, with recovery only becoming evident by 2022. Additionally, other prepared foodstuffs, fats, and oils (SCTG 07) exhibited persistent disruptions in major urban centers, in contrast to the relatively stable or positive trends in agricultural production states, like Iowa, Wisconsin, Texas, and Arkansas.

These observations reflect broader resilience patterns across the network. Agricultural production states such as Iowa or Wisconsin shows relatively rapid and stable recovery, likely supported by the natural resumption of seasonal harvest cycles and the gradual reduction of environmental shocks such as drought or flooding. However, urban logistics hubs and coastal port cities like Los Angeles or New York faced more prolonged and uncertain disruptions. In these areas, recovery was shaped not only by the demand but also by complex interactions among freight infrastructure constraints, institutional policy responses,



and supply chain bottlenecks. Furthermore, shocks occurring in upstream supplier regions would also propagate through the logistics network, adding more uncertainty and risk to the downstream hubs. These differences suggest that regional resilience is shaped not only by local exposure, but also by the functional role of each node within the national food system, and by the primary mechanism, which could be environmental, infrastructural or institutional, that governs each region's vulnerability and recovery pattern.

5 Conclusion

This study quantified how US agri-food flows changed over time and space in response to multiple overlapping shocks between 2018 and 2022. Using annual FAF freight data and a weighted node degree network framework, we examined shifts in domestic, import, and export food movements across regions and commodity groups under the influence of trade disruptions, extreme weather events, and the COVID-19 pandemic. The results show that different regions exhibited varying patterns of disruption and recovery, depending on their commodity profiles, network connectivity, and exposure to specific shock types. These findings demonstrate that large-scale shocks can trigger heterogeneous

responses across the food transport system and highlight the need for regionally differentiated resilience strategies.

Building on these insights, our findings point to several adaptation and policy strategies for improving the resilience of agri-food transportation systems. First, investments that improve routing flexibility at transportation hubs or major cities can help supply chains respond more effectively to disruptions caused by floods, port closures, or other local shocks. Second, states with narrow commodity specialization and limited connectivity (such as Idaho's potato sector) may benefit from added storage or buffer capacity to manage demand fluctuations. Third, encouraging a more diverse and stable mix of domestic and international suppliers can reduce overdependence on a few key nodes.

The limitations associated with this study are as follows. First, because the FAF data are reported annually, our analysis may overlook short-term or seasonal disruptions that occur within the calendar year. For instance, localized floods or droughts that affect spring planting or summer harvest may not appear significant if offset by recovery in later months. Second, the presence of multiple shocks in the same period, for example, the overlap of drought and pandemic in 2021 limits our ability to attribute observed changes to a single cause. Third, while we observe changes in flow volumes and network connectivity, our analysis does not disentangle the underlying drivers of these shifts. In particular, we cannot determine whether observed reductions or recoveries are primarily

due to production-side impacts, transportation disruptions, or external interventions such as policy measures or infrastructure upgrades. The observed network responses may result from a combination of these factors, which cannot be distinguished using flow data alone.

Future research could address these limitations by integrating FAF with higher-frequency datasets such as or spatially explicit datasets, such as monthly freight statistics or satellite-based crop monitoring to improve the temporal resolution of flow analysis. This would help capture short disruptions that are masked in annual aggregates. Additional efforts could focus on developing frameworks to attribute observed changes to specific shock types and on linking empirical flow responses to modeled supply chain dynamics. These advances would enable more precise diagnostics of supply chain behavior under compound risk and inform strategies for designing resilient and adaptive food transport systems.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://faf.ornl.gov/faf5/>.

Author contributions

RZ: Writing – review & editing, Data curation, Methodology, Conceptualization, Visualization, Writing – original draft, Formal analysis. AA: Formal analysis, Visualization, Data curation, Writing – review & editing, Methodology, Conceptualization, Writing – original draft. DK: Conceptualization, Writing – review & editing, Visualization. MK: Writing – original draft, Funding acquisition, Supervision, Methodology, Conceptualization, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This material is based upon work supported by the U.S. Department of Agriculture Grant No. 2023-68012-39076 (Building resilience to shocks and disruptions: Creating sustainable and equitable local and regional food systems in the U.S. Midwest region and beyond).

References

- Aday, S., and Aday, M. S. (2020). Impacts of COVID-19 on food supply chain. *Food Qual. Safety* 4, 167–180. doi: 10.1093/fqsafe/fyaa024
- Anderson, J. D., Mitchell, J. L., and Maples, J. G. (2021). Invited review: lessons from the COVID-19 pandemic for food supply chains. *Appl. Animal Sci.* 37, 738–747. doi: 10.15232/aas.2021-02223
- Barrat, A., Barthélemy, M., Pastor-Satorras, R., and Vespignani, A. (2004). The architecture of complex weighted networks. *Proc. Nat. Acad. Sci.* 101, 3747–3752. doi: 10.1073/pnas.0400087101
- Chappell, B. (2018). *Mexico Hits U.S. Steel and Farm Products With Tariffs, Retaliating for Trump Move*. Washington, DC: National Public Radio (NPR). Available online at: <https://www.npr.org/sections/thetwo-way/2018/06/05/617053788/mexico-hits-u-s-steel-and-farm-products-with-tariffs-retaliating-for-trump-move> (Accessed February 11, 2025).
- Citrus Industry (2023). *U.S. Fresh Oranges Up; OJ Down in 2022–23*. Available online at: <https://citrusindustry.net/2023/12/06/u-s-fresh-oranges-up-oj-down-2022--23/> (Accessed February 11, 2025).
- Colorado General Assembly (2019). *Fy 2019–20 joint budget committee hearing, department of agriculture*.
- Cowley, C. (2020). Reshuffling in soybean markets following Chinese tariffs. *Econ. Rev.* 105, 57–81. doi: 10.18651/ER/v105n1Cowley

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher. All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Author disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s).

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1661492/full#supplementary-material>

- Crimmins, A. R., and Kosmal, A. (2023). *Focus on risks to supply chains*. Technical report, U.S. Global Change Research Program, Washington, DC.
- Davis, K. F., Downs, S., and Gephart, J. A. (2021). Towards food supply chain resilience to environmental shocks. *Nat. Food* 2, 54–65. doi: 10.1038/s43016-020-00196-3
- Doğan, N. B., Mejia, A., and Gomez, M. (2023). Cities can benefit from complex supply chains. *NPJ Urban Sustain.* 3:20. doi: 10.1038/s42949-023-00100-5
- English, B. C., Smith, S. A., Menard, R. J., Hughes, D. W., and Gunderson, M. A. (2022). Estimated economic impacts of the 2019 Midwest floods. *Econ. Disast. Clim. Change* 6, 399–418. doi: 10.1007/s41885-021-00095-2
- Ercsey-Ravasz, M., Toroczka, Z., Lakner, Z., and Baranyi, J. (2012). Complexity of the international agro-food trade network and its impact on food safety. *PLoS ONE* 7:e37810. doi: 10.1371/journal.pone.0037810
- FAF (2020). *Oak Ridge National Laboratory Freight Analysis Framework*. Available online at: <https://faf.ornl.gov/faf5/> (Accessed February 11, 2025).
- Farmonaut (2020). *US-China Trade War's Lasting Impact: How Utah's Agriculture Still Feels the Economic After Shocks*. Farmonaut.
- Fresh Fruit Portal (2025). *Imports Drive Year-Round Availability of Fresh Produce in the US*. Available online at: <https://www.freshfruitportal.com/news/2025/01/21/imports-drive-year-round-availability-of-fresh-produce-in-the-us/> (Accessed February 11, 2025).
- Gomez, M., Mejia, A., Ruddell, B. L., and Rushforth, R. R. (2021). Supply chain diversity buffers cities against food shocks. *Nature* 595, 250–254. doi: 10.1038/s41586-021-03621-0
- Hart, C. E., Hayes, D. J., Jacobs, K. L., Schulz, L. L., and Crespi, J. M. (2020). *The Impact of COVID-19 on Iowa's Corn, Soybean, Ethanol, Pork, and Beef Sectors*. Available online at: <https://card.iastate.edu/home> (Accessed February 11, 2025).
- Hettinger, J. (2020). *With Beef Backlogged and the Market in Flux, Montana Cattle Ranchers Face Tough Choices*. Montana Free Press. Available online at: <https://montanafreepress.org/2020/04/28/with-beef-backlogged-and-the-market-in-flux-montana-producers-face-tough-choices/>
- Hobbs, J. E. (2021a). The covid-19 pandemic and meat supply chains. *Meat Sci.* 181:108459. doi: 10.1016/j.meatsci.2021.108459
- Hobbs, J. E. (2021b). Food supply chain resilience and the COVID-19 pandemic: what have we learned? *Canadian J. Agric. Econ.* 69, 189–196. doi: 10.1111/cjag.12279
- Johnson, R., and Monke, J. (2019). *Federal crop insurance: Record prevent plant acres and payments in 2019*. Technical Report R46180, Congressional Research Service.
- Karakoc, D. B., and Konar, M. (2025). Trade-offs between resilience, sustainability and cost in the U.S. agri-food transportation infrastructure. *Nature Food* 6, 401–409. doi: 10.1038/s43016-025-01128-9
- Karakoc, D. B., Konar, M., Puma, M. J., and Varshney, L. R. (2023). Structural chokepoints determine the resilience of agri-food supply chains in the united states. *Nat. Food* 4, 607–615. doi: 10.1038/s43016-023-00793-y
- Karan, E. P., Asgari, S., and Asadi, S. (2023). Resilience assessment of centralized and distributed food systems. *Food Secur.* 15, 59–75. doi: 10.1007/s12571-022-01321-9
- Kaufman, J. (2025). *High-Value Products Drive Growth in U.S. Agricultural Imports*. Available online at: <https://www.ers.usda.gov/data-products/ag-and-food-statisticscharting-the-essentials/agricultural-trade> (Accessed February 11, 2025).
- Kayne, P. (2020). *Pandemic hurting local ranchers*. Casper, WY: Wyoming Livestock Roundup.
- Leeds School of Business, University of Colorado Boulder (2019). *Colorado business review*. Business Research Division, University of Colorado.
- Luckstead, J., Nayga, R. M., and Snell, H. A. (2021). Labor issues in the food supply chain amid the COVID-19 pandemic. *Appl. Econ. Perspect. Policy* 43, 382–400. doi: 10.1002/aep.13090
- Melton, A., and Cooke, B. (2018). *Reduced exports to china in fiscal year 2019 may drive U.S. agricultural trade balance to lowest level since 2007*. U.S. Department of Agriculture Economic Research Service.
- Morgan, S., Arita, S., Beckman, J., Ahsan, S., Russell, D., Jarrell, P., et al. (2022). *The economic impacts of retaliatory tariffs on u.s. agriculture*. Technical Report ERR-304, U.S. Department of Agriculture, Economic Research Service.
- National Centers for Environmental Information (NCEI) (2021). *National Climate Report: August 2021*. Asheville, NC: National Oceanic and Atmospheric Administration (NOAA). Available online at: <https://www.ncei.noaa.gov/news/national-climate-202108>
- National Centers for Environmental Information (NCEI) (2023). *Assessing the u.s. climate in 2022*. Technical report.
- National Centers for Environmental Information (NCEI), NOAA (2020). *Historic midwest floods of 2019: Final report*. Technical report.
- National Oceanic and Atmospheric Administration (2023). *Assessing the u.s. climate in 2022*. NOAA NCEI.
- National Weather Service (NWS) (2019). *Spring Flooding Summary 2019*. Available online at: https://www.weather.gov/dvn/summary_SpringFlooding_2019 (Accessed February 11, 2025).
- Nebraska Farm Bureau (2022). *Drought in 2022*.
- Newton, J. (2019). *Reviewing County-Level Corn and Soybean Yields in 2018*. Washington, DC: American Farm Bureau Federation. Available online at: <https://www.fb.org/market-intel/reviewing-county-level-corn-and-soybean-yields-in-2018> (Accessed February 11, 2025).
- Nigh, V. (2023). *Record Numbers Not the Only Striking Thing About 2022 U.S. Ag Trade*. Available online at: <https://www.fb.org/market-intel/record-numbers-not-the-only-striking-thing-about-2022-u-s-ag-trade> (Accessed February 11, 2025).
- Numbers, C. (2021). *State exports take a hit in 2020; covid drives 15% drop*. Available online at: <https://ctbythenumbers.news/ctnews/state-exports-take-a-hit-in-2020-covid-drives-15-drop>
- Office of the United States Trade Representative (2020). *Economic and trade agreement between the United States of America and the people's Republic of China (phase one)*. USTR.
- Opsahl, T., Agneessens, F., and Skvoretz, J. (2010). Node centrality in weighted networks: Generalizing degree and shortest paths. *Soc. Netw.* 32, 245–251. doi: 10.1016/j.socnet.2010.03.006
- Opsahl, T., Colizza, V., Panzarasa, P., and Ramasco, J. J. (2008). Prominence and control: The weighted rich-club effect. *Phys. Rev. Lett.* 101:168702. doi: 10.1103/PhysRevLett.101.168702
- Paul Schattenberg (2023). *U.S. Fresh Produce Imports to Exceed \$53 Billion by 2030*. Available online at: <https://www.farmprogress.com/vegetables/u-s-freshproduce-imports-to-exceed-53-billion-by-2030> (Accessed February 11, 2025).
- Randall, S. (2019). *Federal crop insurance: Record prevent plant (ppl) acres and payments in 2019*. Technical Report R46180, Congressional Research Service.
- Reuters (2019). *Timeline: Key Dates in the U.S.-China Trade War*. London: Reuters.
- Specialty Crop Grower (2023). *USDA Report: Fresh Vegetable Imports Up in 2022*. Available online at: <https://specialtycropgrower.com/usda-report-fresh-vegetableimports-up-in-2022/> (Accessed February 11, 2025).
- Toth, M. (2021). *Minnesota Exports Fell 10% in 2020: Covid-19 Caused Delays and Uncertainty in the International Market*. Available online at: <https://www.logisticsmonthly.com/business/minnesota-exports-fell-10-in-2020/> (Accessed February 11, 2025).
- U.S. Department of Agriculture, Economic Research Service (ERS). (2023). *Food and Consumers: COVID-19 Pandemic Impact on Food Spending and Markets*. Washington, DC: U.S. Department of Agriculture. Available online at: <https://www.ers.usda.gov/covid-19/food-and-consumers> (Accessed February 11, 2025).
- U.S. Department of Agriculture, Farm Service Agency (FSA) (2019). *Report: Farmers Prevented From Planting Crops on More Than 19 Million Acres*. Washington, DC: U.S. Department of Agriculture. Available online at: <https://www.fsa.usda.gov/news-events/news/08-12-2019/report-farmers-prevented-planting-crops-19-million-acres> (Accessed February 11, 2025).
- U.S. Department of Agriculture, Foreign Agricultural Service (FAS) (2020). *2019 U.S. agricultural export yearbook*.
- U.S. International Trade Commission (2019). *Shifts in U.S. Merchandise Trade 2019: Agricultural Products*. Washington, DC: U.S. International Trade Commission. Available online at: https://www.usitc.gov/research_and_analysis/trade_shifts_2019/agriculture.htm (Accessed February 11, 2025).
- US Department of Agriculture, National Agricultural Statistics Service (2022). *Colorado crop progress and condition - week ending March 13, 2022*.
- USDA National Agricultural Statistics Service (2021). *South Dakota Crop Progress and Condition — Week Ending September 19, 2021*. USDA NASS Weekly Report (News Release), Sioux Falls, SD.
- Wang, J., and Dai, C. (2021). Evolution of global food trade patterns and its implications for food security based on complex network analysis. *Foods* 10:2657. doi: 10.3390/foods10112657
- Wojtanik, R. (2019). *Fruitful Summer: Cherry Crops a Sweet Success*. Journal of Business.
- World Health Organization (2020). *WHO Director-General's Opening Remarks at the Media Briefing on COVID-19 - 11 March 2020*. Geneva: World Health Organization. Available online at: <https://www.who.int/news-room/speeches/item/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020> (Accessed February 11, 2025).
- World Health Organization (2023). *Statement on the fifteenth meeting of the ihr (2005) emergency committee on the COVID-19 pandemic*. WHO Official Communication.
- Yao, P., Fan, H., Wu, Q., Ouyang, J., and Li, K. (2023). Compound impact of COVID-19, economy and climate on the spatial distribution of global agriculture and food security. *Sci. Total Environ.* 880:163105. doi: 10.1016/j.scitotenv.2023.163105
- Zhang, D., Jiang, D., and He, B. (2025). Empowering agricultural economic resilience with smart supply chain: theoretical mechanism and action path. *Sustainability* 17:2930. doi: 10.3390/su17072930