nature food

Analysis

https://doi.org/10.1038/s43016-025-01128-9

Trade-offs between resilience, sustainability and cost in the US agri-food transportation infrastructure

Received: 5 September 2023

Accepted: 22 January 2025

Deniz Berfin Karakoc[1,2] & **Megan Konar**[1]

Agricultural and food supply chains in the United States are essential for both global and local food security, yet the transportation of agri-food commodities has received little attention despite being an essential feature for connecting production to consumption. Here we map the US agri-food distribution onto real-world highways, railways and waterways and also quantify the trade-offs between cost, path redundancy and carbon emissions of agri-food transit across transportation modes. Highways show the greatest path redundancy; relative to waterways, highways also cost 3 orders of magnitude more and emit 60 times more carbon. On the contrary, waterways show the lowest cost and emission levels, but path redundancy against transportation disturbances is 80% lower than for highways. Railways offer a middle ground on path redundancy, carbon emission and cost concerns compared to highways and waterways. Our findings can inform efforts to balance affordability, resilience and sustainability in agri-food transportation.

The United States is central to well-connected global food supply chains[1]. The United States is the largest exporter of cereal grains and a net importer of vegetables and fruits[2]. Domestic infrastructure enables the United States to provide stable, affordable and accessible national and global food supplies[3,4]. The US Government also actively leads food security initiatives at both local and global scales, such as the Protecting America's Food and Agriculture Act[5] and Global Food Security Strategy[6]. Therefore, detailed information on agri-food movements for import, export and domestic consumption within the United States is essential not just for national[7] but also for global policies[8,9] regarding food supply chain resilience.

The majority of food supply chain resilience studies focus on agricultural production in light of production shocks[10–12]. However, growing threats, such as pandemics[13,14] and cyber-terrorist attacks[15,16], could impose substantial perturbations within the distribution step of agri-food supply chains. Yet, existing studies of agri-food transit resilience do not include flows along the real-world transportation infrastructure[17–19]. Evaluating transport by mode would enable an assessment of the cost and efficiency of transit[20,21], as well as an understanding of the relationship between efficiency and resilience[22]. Thus, assessing real-world agri-food transit by mode within one of the largest trade powers—the United States—would fill an important research gap.

So far, logistics researchers have modelled how food flows from producers to consumers in the United States at a fine spatial scale[23], with consideration of time[24], and for specific agri-food commodities[25]. However, these models are waiting to be mapped over real-world infrastructures. It is worth noting that studies have not yet examined how different transportation modes support agri-food transit for export, import and domestic consumption. Government reports have highlighted the contribution of railways to moving grain[26] and of highways to all freight[27]. These reports also indicate how barges move large quantities of bulk commodities at a relatively low cost[28]. However, there has not yet been a coherent and consistent study for all agri-food commodities on all transportation modes (highways, railways, waterways) for all flow types (domestic, import, export) for an entire country. Therefore, assessing the contribution of each transportation mode to

---

[1]The Grainger College of Engineering, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA. [2]School of Computing and Augmented Intelligence, Arizona State University, Tempe, AZ, USA. e-mail: mkonar@illinois.edu

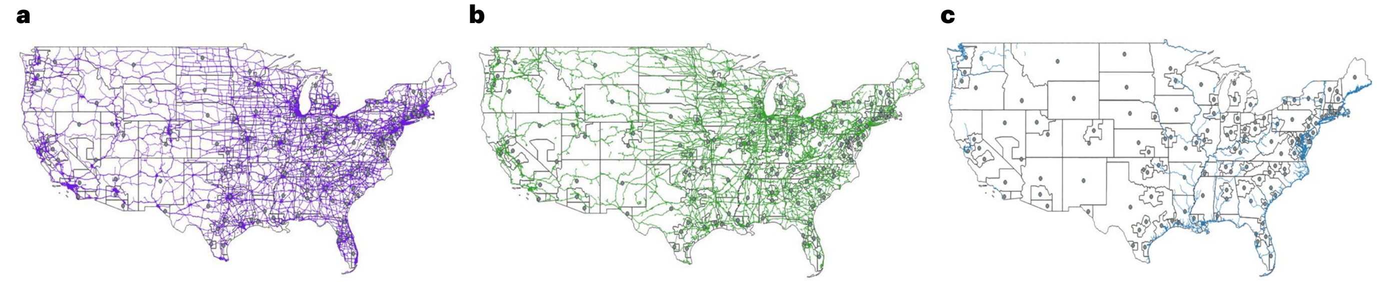

Fig. 1 | Base maps of transportation modes. **a**–**c**, Highways (**a**), railways (**b**) and waterways (**c**) in the CONUS with their corresponding FAF regions. Spatial data of transportation infrastructure are obtained from the US Department of Transportation[45], and spatial data of FAF geographic regions are obtained from the US Census Bureau[29]. Grey circles indicate geographic centroids of FAF regions.

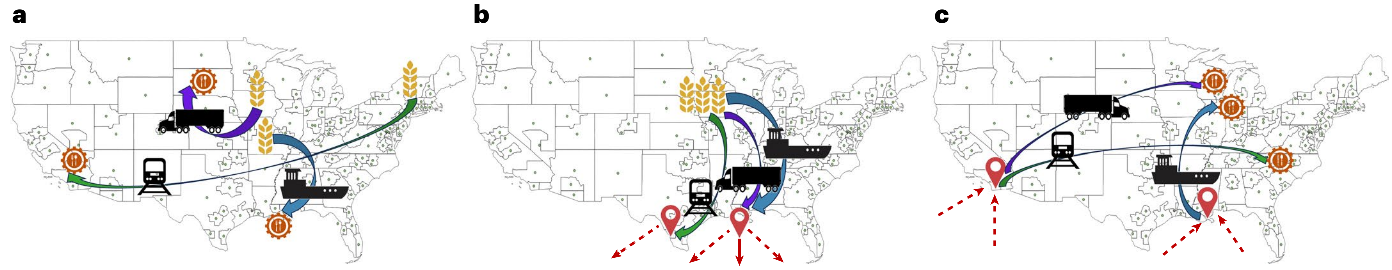

Fig. 2 | Our scope of our agri-food re-distribution within the United States. **a**–**c**, Sample illustrations of agri-food re-distribution within the United States for domestic (**a**), export (**b**) and import (**c**) flows across transportation modes. Our scope is mapping by mode movement of locally produced commodities for local consumption (**a**), locally produced commodities to US port of exit to be consumed abroad (**b**) and finally non-locally produced commodities from US port of entry to be consumed locally (**c**).

the entire agri-food supply chain, including their efficiency, resilience and sustainability characteristics, would improve our understanding of US food supply chains, for both local and global food security.

The goal of this study is to comprehensively quantify the contribution of transportation infrastructure to the agri-food supply chain of the continental United States (CONUS); that is, Alaska and Hawaii are not included[29]. Through developing a unified framework of data analytics, network science and geographic information science techniques, we map the agri-food load to real-world highway, railway and waterway networks. Based on our findings, we then quantify the trade-off between economic efficiency, resilience and sustainability for agri-food transit across these transportation modes. In this Article, we define the total cost of transit as the economic efficiency, total carbon dioxide emission as the sustainability, and transit re-routing capacity as the resilience for each transportation mode. The research questions that guide this study of mapping agri-food flows on multi-modal transportation infrastructure in the United States are the following: (1) How are agri-food flows distributed across transportation modes? (2) How do transportation modes support domestic, import and export flows of agri-food? (3) What is the trade-off between economic efficiency, resilience and sustainability across transportation modes?

Results

Agri-food flows across transportation modes

The individual modal networks that we generate and map the agri-food flows on are illustrated in Fig. 1. These highways, railways and waterways correspond to the transportation infrastructure-specific paths between every Freight Analysis Framework (FAF)[30] region to re-distribute agri-food commodities within the US origins and destinations. As summarized in Fig. 2, we only focus on the agri-food movement that takes place on inland highways, railways and waterways of the United States for each flow type (domestic, export, import). Thus, we do not consider the international trade part of the import and export flows.

The total agri-food movements are 2.94×10^9 tons (1 ton = 1,000 kg) on the highways, 3.27×10^8 tons on the railways and 1.42×10^8 tons on the waterways. In Fig. 3, we evaluate the total mass flux on each transportation modal network across flow types (that is, domestic, import and export) and commodities, which are listed in Table 1. The total mass flux of domestically produced and consumed agri-food commodities within the United States is the highest, 3.08×10^9 tons. It is followed by export flows which represent the domestically produced agri-food commodities within the United States that are being delivered to the US port of exit. From there, they will be exported abroad for consumption. The total mass flux of exported agri-food commodities is 2.42×10^8 tons. The lowest total mass across flow types is for import flows, which is 7.95×10^7 tons. Imported agri-food commodities are produced abroad, brought to US ports of entry and then re-distributed within the United States for consumption. These findings are consistent across transportation modes where the highest food transit fraction on each transportation mode (that is, highways, railways and waterways) is for domestic flows. Then, it is followed by export and import flows.

Figure 3 shows that highways carry the most agri-food mass across all commodities and flow types. However, the proportion of cereal grains (Standard Classification of Transported Goods (SCTG) 02) along the railways and waterways is higher than it is on the highways. For example, 57.99% and 51.61% of all agri-food movement is cereal grains along the railways and waterways, respectively. For the highways, this value is 34.74%. Furthermore, the proportion of agricultural products (SCTG 03) over the total mass of agri-food transit is higher in waterways than it is in railways and highways. About 37.75% of all waterway food transit is SCTG 03, which contains soy[31], and can be explained by the

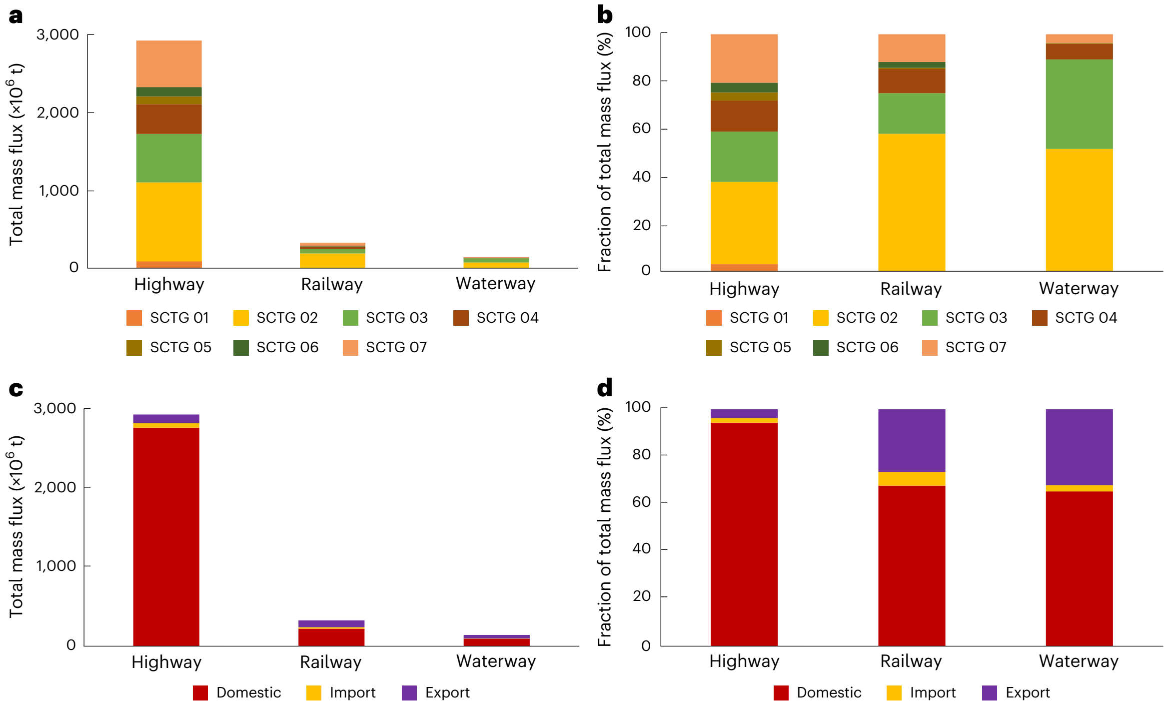

Fig. 3 | Breakdown of empirical agri-food flows data. a–d, FAF scale agri-food flow across transportation modes by SCTG group (**a**,**b**) and flow type (**c**,**d**). Both total mass in million tons (**a**,**c**), and fraction of total mass in percentage (**b**,**d**) are plotted. The 2017 empirical data for FAF-scale agri-food flows are obtained from OakRidge National Laboratory[30]. SCTG 01, live animals; SCTG 02, cereal grains; SCTG 03, agricultural products; SCTG 04, animal origin products; SCTG 05, meats and their preparations; SCTG 06, milled grain products; SCTG 07, other prepared foodstuff. For a detailed explanation of SCTG commodity groups, refer to Table 1.

Table 1 | List of the considered food commodity groups, according to the SCTG

SCTG	Food commodity
01	Live animal and fish
02	Cereal grains
03	Agricultural products (includes fruits and vegetables, as well as soy)
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

More detailed commodity breakdowns are available in the US Census Bureau[53].

export flows of soy through the Mississippi River, helping the United States remain competitive in global soy markets[32]. On the contrary, certain agri-food commodities that need ventilation (that is, SCTG 01—live animals) or temperature control (that is, SCTG 05—meat and their preparations) are not distributed through railways or waterways at all during the region-to-region transit.

Agri-food flow types across transportation modes

The total mass flux of agri-food for each FAF region across transportation modes and flow types is shown in Fig. 4. Figure 4a–c illustrates the total mass flux (inflows and outflows aggregated) along highways for domestic, export and import flows, respectively. For domestic flows, FAF regions located in the Midwest, especially in the Corn Belt, have the highest total mass flux by highways. For export flows, New Orleans, Louisiana, Los Angeles, California, and Seattle, Washington FAF regions are highlighted with the highest total mass flux by highways. Lastly, for import flows, FAF regions on the US–Mexican and US–Canadian borders are observed to in-take and out-take the highest total agri-food flux by highways.

Similar trends are observed for total agri-food flux by railways within the CONUS. Particularly for railways, domestic flows are accumulated around the Midwest, export flows are the highest in Texas FAF regions, and finally, majority of the agri-food flux is imported through the Northern FAF regions on the US–Canadian border as seen in Fig. 4d–f, respectively. Waterways show the most variable spatial trends in the transport of agri-food. The highest total mass flux occurs along the Mississippi River and East Coast FAF regions for domestically produced and consumed food commodities. The highest total mass flux for exports is located in New Orleans, LA, and Texas FAF regions. Lastly, California, Florida, Buffalo, NY and New Orleans, LA, FAF regions have the highest total mass flux for the imported agri-food commodities.

Furthermore, we map agri-food flows to the real-world transportation infrastructure in Fig. 5. In Fig. 5, the top 100 mass movements between origin and destination FAF regions are mapped on highways, railways and waterways across flow types. It is worth noting that the mass flux has been scaled across transport modes for easy visual comparison. We observe that inland waterways dominate as the main domestic agri-food transit corridor in terms of top 100 mass, especially the Mississippi River, as seen in Fig. 5a. Railways generally transport the major domestic agri-food flows between the East Coast and West Coast. By contrast, domestic mass movement along the highways takes place between nearby locations that are generally around the Midwest and Californian FAF regions.

For the export flows, the top 100 mass movement is seen in Fig. 5b. In particular, highways that connect the CONUS to the Port of New Orleans represent the major pathways of agri-food export. Highways

https://doi.org/10.1038/s43016-025-01128-9

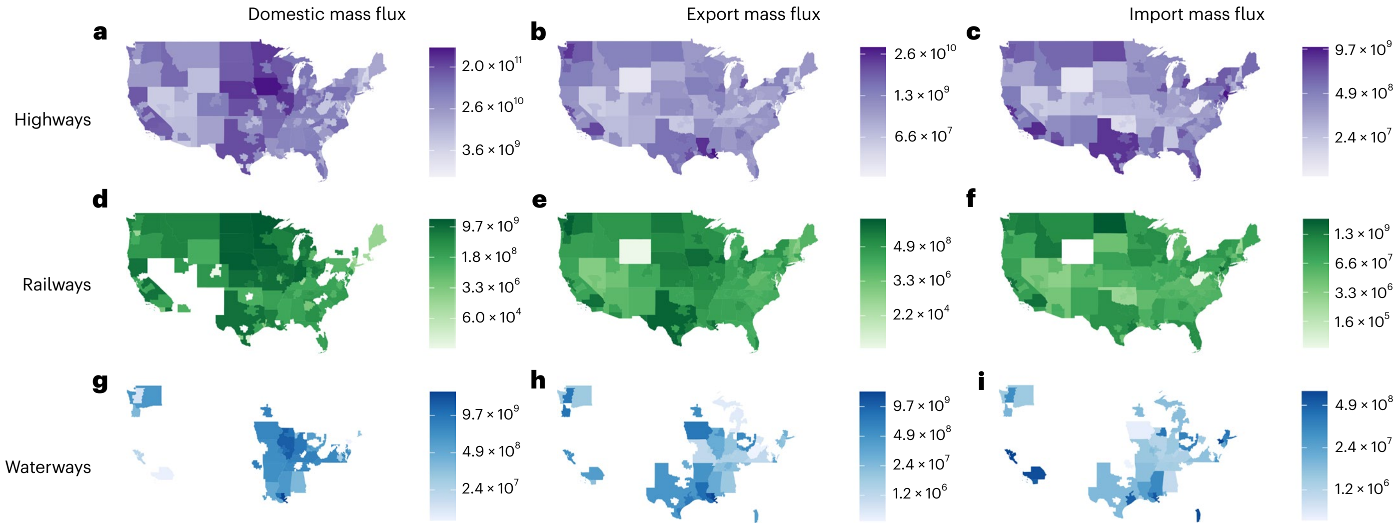

Fig. 4 | Heat maps of total agri-food mass flux (kg) across transportation modes by flow type at FAF scale. a–c, Agri-food mass flux by highways, **d–f**, agri-food mass flux by railways and **g–i**, agri-food mass flux by waterways. Domestic agri-food mass flux (**a**,**d**,**g**), export agri-food mass flux (**b**,**e**,**h**) and import agri-food mass flux (**c**,**f**,**i**).

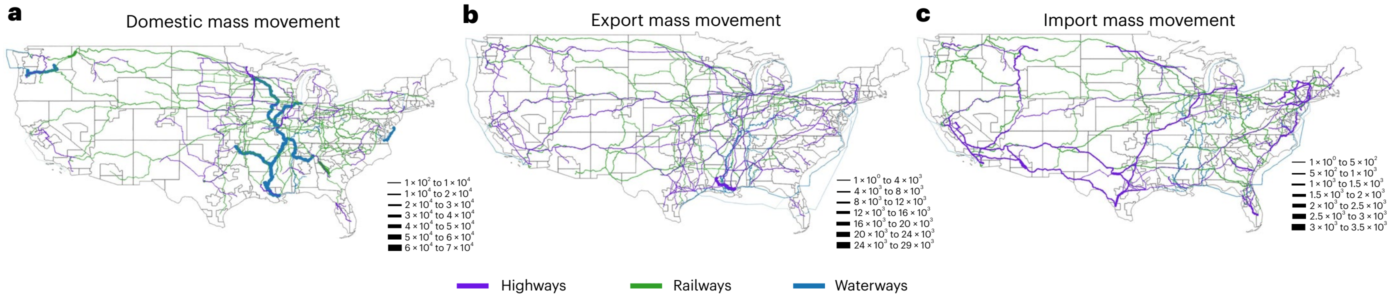

Fig. 5 | Agri-food flows by mode and flow type. a–c, Domestic (**a**), export (**b**) and import (**c**) agri-food flows through highways, railways and waterways within the CONUS. Top 100 mass movements (except the self-loops) are plotted for each mode and flow type combination. Darker and thicker purple, green and blue links represent higher food flux (kilotons) transport through inland highways, railways and waterways, respectively.

along the US–Canadian border and California FAF regions are also important for export flows. Railway distribution of major export flows mainly connects the Midwest to the West Coast—collecting agri-food commodities from the supply locations and delivering them to destination ports that will further transport to final consumption points abroad. However, waterways do not contribute to the collection of agri-food commodities within the United States for export as much as highways and railways. Note that this finding is only for the re-distribution of locally produced agri-food within the United States before it is further exported abroad.

Lastly, highways are the main transportation mode for imports that are produced abroad and re-distributed within the United States. Highways that are located on the US–Mexican and US–Canadian borders, that is, within California, Texas, New Mexico, Arizona and Upstate New York FAF regions, move the top 100 imported mass. Similarly, railways that are close to the US–Canadian border, as well as located in California and Midwest FAF regions, carry the heaviest agri-food imports. Waterways are used less for imports than exports, which is also substantially less than the domestic flows. This is due to the fact that the Port of New Orleans is a major destination for domestically consumed and exported commodities rather than an origin for imported commodities, as commodities are brought there through the Mississippi River. For imported commodities, the major ports of entry are located along the US land borders.

These findings highlight the importance of each FAF region and their corresponding ports for different flow types. Our results particularly emphasize the criticality of the Port of New Orleans for all agri-food transit—domestic, export and import—agnostic to its connecting transportation mode. Furthermore, we draw a spatially detailed picture of the importance of each transportation infrastructure for the movement of agri-food commodities across flow types (refer to the Supplementary Information for our analysis broken down by each agri-food commodity group individually). In light of our results, future research and policy could propose more tailored infrastructure investments to ensure resilient and secure food supply chains within the United States.

Trade-off across transportation modes

We quantify the economic efficiency, resilience and sustainability characteristics of each agri-food transit network. As seen in Table 2, highways move agri-food commodities at the highest total cost and carbon emissions. This is due to the fact that highways carry the highest total mass at the highest unit cost and the highest unit CO_2 emission per ton-mile (1 ton-mile is the equivalent of shipping 1 ton of product, 1 mile). Highways are followed by railways and then waterways in descending order of total cost and carbon emissions. This is expected since railways carry a larger total mass of agri-food commodities at a higher unit cost and unit CO_2 emission than waterways.

Table 2 | Total cost of agri-food transport, path redundancy of the transportation network, evenness of the agri-food flow and total carbon emission of the agri-food transit within the transportation network, per mode, *m*

Mode	Unit cost (US$)	Total mass (tons)	Total cost (US$)	Redundancy	Evenness	Unit CO_2 (g)	Total CO_2 emission (tons)
Highways	3.880	2.94×10^9	2.65×10^{12}	4.06	2.52	140.70	9.59×10^7
Railways	0.050	3.27×10^8	1.21×10^{10}	3.35	2.38	21.57	5.20×10^6
Waterways	0.016	1.42×10^8	1.70×10^9	2.19	1.54	15.08	1.60×10^6

The total cost (US$) accounts for the economic efficiency, E^m; redundancy accounts for the existence of alternative paths, R^m; H^m accounts for the evenness of mass flow; and total CO_2 emissions (tons), S^m, account for the sustainability. Higher E^m represents more costly (less efficient) agri-food distribution. Higher R^m and H^m represent higher redundancy and evenness (more resilient). Higher S^m represents more carbon emission (less sustainable).

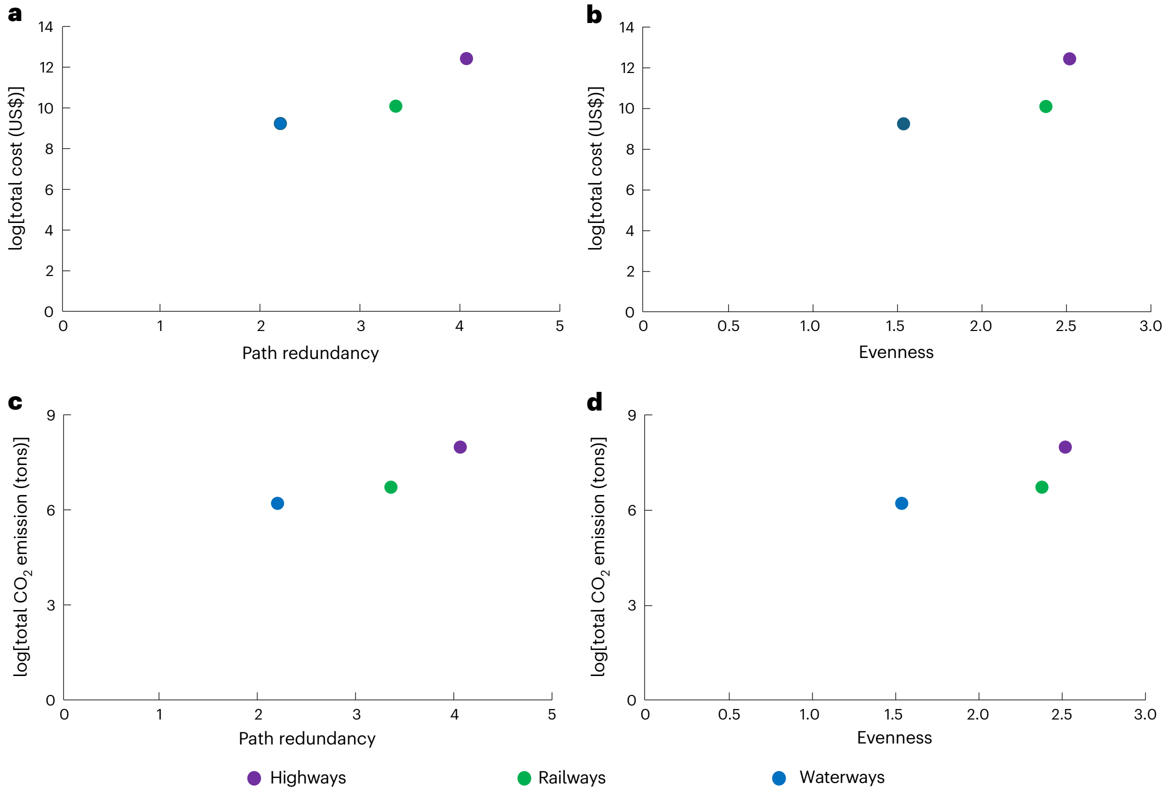

Fig. 6 | Trade-off between efficiency, resilience and sustainability by transportation mode. a–d, Economic efficiency is represented through the total cost of food transit (US$) (at log scale for clear visualization) (**a**,**b**); for resilience, path redundancy represents the existence of alternative routes to connect any origin and destination in case of disruption along the network (**a**,**c**), and evenness represents the homogeneously contributed agri-food flow between multiple origin and destination pairs (**b**,**d**). Lastly, sustainability is represented through the total CO_2 emission of food transit (tons) (at log scale for clear visualization) (**c**,**d**). In **a** and **b**, higher *y*-axis values denote lower economic efficiency; however, higher *x*-axis values denote higher path redundancy and evenness. In **c** and **d**, higher *y*-axis values denote a less sustainable form of transit; however, higher *x*-axis values denote higher path redundancy and evenness.

For the resilience of agri-food transit networks, highways have the highest number of alternative routes, that is, capacity for re-routing flows, between any origin and destination pairs. With higher redundancy—existence of multiple paths between any supply and demand points—highways are more resilient against a disturbance on one of the connecting roads, as alternative paths exist. The path redundancy of railways is calculated to be lower than highways, and waterways have the lowest redundancy.

For the evenness of agri-food transit per mode, in highways multiple origins provide commodities to multiple destinations in similar amounts. Thus, agri-food transit is more evenly distributed between FAF regions. In railways, evenness decreases, which means that a lower number of FAF regions participate in agri-food transit through rail lines; that is, the food flow concentration among the FAF regions is not as homogeneous as it is on highways. Finally, waterways have the lowest evenness as monopoly in contribution to food flow per FAF region is the highest. This is mainly caused by natural constraints, that is, not every FAF region has access to inland waterways, and cereal grain production is concentrated in the US Midwest[33].

Thus, our results reveal that economic efficiency and resilience, as well as sustainability and resilience, are competing goals across transportation modes for agri-food transit, as seen in Fig. 6. The real-world distribution by mode indicates that reach and ease of transit may be a higher priority than cost or emission concerns. However, this is partly due to the characteristics of certain food commodities that require temperature-controlled or ventilated transportation, making transit through railways or waterways infeasible.

Discussion

It will be increasingly important to balance affordability, resilience and sustainability in agri-food transit going forward. Following the COVID-19 pandemic, food price inflation soared, serving as a reminder of the importance of maintaining affordable food supplies for domestic and international food security[34]. Restoration, expansion and modernization investments in infrastructure, and strategic policy choices are needed to ensure that agri-food transportation continues to be safe, secure and affordable.

Investments in waterways infrastructure, such as modernizing locks, restoring dams and ports and deepening crucial waterway chokepoints (for example, Locks 52 and 53 on the Mississippi River) can improve cargo flow and increase the ability for agricultural shippers to use waterways to their full capacity[35]. Food spoilage in refrigerated trucking may be exacerbated with the increase in the ambient temperature due to climate change in the future. Investing in green innovations for refrigerated trucks would help to address food safety and security concerns in light of sustainability goals[36], also reducing food loss and waste. Railroads operate on an expansive nationwide network that is exposed to increasingly frequent climate-driven natural disasters[37,38]. Investments in rail networks, such as digital integration, new and higher-capacity equipment, implementation of additional double tracks, and extended yard tracks to move load faster can enhance the reliability of railroads for agri-food transit going forward[39].

Even though transport emissions make up a relatively small portion of the carbon footprint of the entire food system[40], it is important to evaluate all opportunities to reduce carbon emissions along these essential supply chains[41,42]. This is especially critical within the United States, as emissions from all agri-food transport in the United States total over 100 million tons[43]. This is more than the total annual emissions of some countries, such as Colombia and Belgium[44]. As efforts intensify to decarbonize the economy, including the food systems, there is a need to determine opportunities to enhance sustainability throughout all aspects of agri-food supply chains—including their transit—without sacrificing resilience or affordability (refer to the Supplementary Information for a more detailed discussion).

Conclusion

In this study, we map agri-food flows onto real-world transportation infrastructure within the United States. We observe that the majority of the total mass flux moves along the highways, agnostic to the food commodity and flow type. For domestic agri-food flows, inland waterways shift the bulk of food, with the Mississippi River as the backbone of transit. For exported agri-food, highways connecting the interior United States to the Port of New Orleans carry the largest flow masses; however, for imported agri-food, highways located within California and along the US–Mexican border carry the greatest bulk of agri-food goods.

We also quantify the relationship between economic efficiency, resilience and sustainability across transportation modes. Waterways ensure the lowest total cost and carbon emissions of agri-food transit but have the lowest ability to re-route in case of a disruption. On the contrary, highways provide the highest re-routing ability but at the highest total cost and carbon emissions. Future research and decision-making can consider these trade-offs between economic efficiency, resilience and sustainability in supply chain transportation for achieving food security objectives.

Methods

Here we explain our input data, approach to mapping agri-food flows on transportation infrastructure within the CONUS and economic efficiency versus path redundancy versus carbon emission trade-off analysis across modes. See the Supplementary Information for a more detailed explanation.

Input data

This study has two sets of input data: 2017 agri-food flows at FAF-scale and 2015 transportation infrastructure shapefiles within the United States. FAF data for 2017 are the most up-to-date empirical data that are created through a partnership between the US Bureau of Transportation Statistics and the Federal Highway Administration[30]. FAF-scale data provide information on the domestic and international transfer of commodities by the SCTG, as listed in Table 1, for the US FAF regions along highways, railways and waterways individually. We use FAF-scale data for re-distribution of the (1) domestically produced and consumed, (2) imported and (3) exported agri-food commodities per transportation mode within the United States. Note that the import flows indicate 'agri-food movement within the United States after the commodities enter the domestic port'. Similarly, the export flows indicate 'agri-food movement within the United States before the commodities exit the domestic port'. Thus, we always focus on the agri-food re-distribution within the United States. Lastly, FAF data do not include last-mile delivery. These are region-to-region agri-food transit information.

For the second set of data, we use the shapefiles of CONUS highways, railways and waterways from the National Transportation Atlas Database (NTAD) developed by the US Department of Transportation, Bureau of Transportation Statistics[45]. The 2015 NTAD, the most up to date, is a nationwide geographic dataset of transportation infrastructure. This dataset includes spatial information for transportation modal networks, as well as the related attributes for these features such as distances in miles. We limit our NTAD data for (1) interstate and non-interstate highways, (2) Class I–II–III rail lines and (3) inland waterways to be consistent with the Bureau of Transportation Statistics' reports[46].

Mapping agri-food flows on transportation modes

We convert shapefile datasets into transportation networks through a crosswalk between GIS software (QGIS) version 3.28.2 and network analysis software (RStudio) version 4.0.2. We generate an individual network for each transportation mode, where each spatial line represents a network link and the connection point of two adjacent links represents a network node. The distance information in miles for each spatial line is captured as the network link weight. For each transportation mode, we identify the network node that is closest to the geographic centroid of each FAF region. These network nodes—closest to FAF geographic centroids—are adopted as the FAF region-specific origin and destination points. Thus, the mode-specific networks are reduced to 129 nodes, each one representing a unique FAF region.

Once the transportation mode-specific networks are created, we then proceed with computing the shortest paths between every origin and destination pair along the real-world infrastructure, according to the real-world distance in miles. We assume that agri-food flows per transportation mode move along the minimum total distance, which is reasonable as this is typically the most cost-effective path. Finally, the empirical agri-food flows between FAF regions per SCTG commodity are accumulated to compute the aggregated flow of all agri-food commodities between each FAF origin–destination pair.

Efficiency, resilience and sustainability trade-off

We develop efficiency, resilience and sustainability measures to specifically account for the transportation of agri-food commodities. We calculate the total cost to account for the efficiency of agri-food transit on each real-world transportation network. The mode-specific total cost of agri-food transit, E^m, is formulated as in equation (1) where m is the transportation mode (that is, highways/railways/waterways), W is the mass flux (tons) and D is the real-world distance (miles) between each FAF-scale origin i and destination j pair. Finally, c is the unit cost of transit per ton-mile specific to each mode. The most up-to-date (that is, 2015) unit cost per mode values are derived from previous literature[47], and we define the higher total cost of transit (US$) to be economically less efficient[48].

$$E^m = \sum_{ij} W_{ij}^m \times D_{ij}^m \times c^m \tag{1}$$

To quantify the resilience of mode-specific real-world networks for agri-food transit, we compute the path redundancy between every origin and destination pair. The redundancy metric refers to the replication of pathways which enhances the fault tolerance of the network. In case a disturbance or shock occurs on one of the paths that connect an origin–destination pair, the existence of alternative paths—additional redundancy—permits the transit of goods to continue[49]. The formula for mode-specific redundancy of agri-food transit networks, R^m, is adopted from the literature [50], as seen in equation (2). Here, a dot in the place of an index represents the summation of that index, and ln represents natural logarithm. Networks with higher values of redundancy metric, R^m, are defined to be more resilient, in case of perturbations (refer to the Supplementary Information for a detailed interpretation of redundancy metric, R^m).

$$R^m = -\sum_{ij} \frac{W_{ij}^m}{W_{..}^m} \ln \frac{W_{ij}^m W_{ij}^m}{W_{.j}^m W_{i.}^m} \tag{2}$$

For resilience, we also compute the Shannon diversity index, H^m, of the mode-specific empirical agri-food transit networks as seen in equation (3). Similar to equation (2), the proportion of the mass contribution of flow from origin i to destination j relative to the total mass movement in the network is used here. The Shannon diversity index quantifies how evenly the agri-food flow between origin and destination pairs is distributed, as well as the homogeneity of the proportion of mass contribution. Higher values of H^m indicate more evenly distributed flow contributions across the network components[51], which also indicates more resilient networks against disruptions.

$$H^m = -\sum_{ij} \frac{W_{ij}^m}{W_{..}^m} \ln \left(\frac{W_{ij}^m}{W_{..}^m} \right) \tag{3}$$

Lastly, we quantify the total carbon emissions associated with agri-food transportation for each transportation mode. Total carbon emissions of agri-food transit for each mode, S^m, is formulated in equation (4), which is similar to the total transit cost calculations (equation (1)). But now e is the CO_2 emission coefficient per unit ton-mile specific to each mode. Mode-specific unit CO_2 emission coefficients are collected from the literature[52] where higher total carbon emissions (tons of CO_2) represent less sustainable modes of transit.

$$S^m = \sum_{ij} W_{ij}^m \times D_{ij}^m \times e^m \tag{4}$$

The goal of the trade-off analysis is to quantify how different transportation modes balance resilience, efficiency and sustainability concerns. Therefore, all the measures are calculated individually for highways, railways and waterways to determine how these different objectives of agri-food transit vary by mode.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data sources are listed in the Methods section of the paper and are freely available online. FAF-scale food flows data are collected from https://faf.ornl.gov/faf5/Default.aspx. The spatially located shapefiles of US highways, railways and waterways are collected from https://rosap.ntl.bts.gov/view/dot/7547.

Code availability

Code for mapping the agri-food movement onto real-world transportation infrastructure and analysing the trade-off between efficiency, resilience and sustainability among the transportation modes in this study is developed in QGIS version 3.28.2 and RStudio version 4.0.2. All code will be made available upon reasonable request from the corresponding author.

References

1. Ercsey-Ravasz, M., Toroczkai, Z., Lakner, Z. & Baranyi, J. Complexity of the international agro-food trade network and its impact on food safety. *PloS ONE* **7**, e37810 (2012).
2. *Trade of Agricultural Commodities 2000–2022*. Technical report, FAOSTAT ANALYTICAL BRIEF 44 (Food and Agriculture Organization of the United Nations, 2022).
3. Ericksen, P. J. Conceptualizing food systems for global environmental change research. *Global Environ. Change* **18**, 234–245 (2008).
4. Falkendal, T. et al. Grain export restrictions during COVID-19 risk food insecurity in many low-and middle-income countries. *Nat. Food* **2**, 11–14 (2021).
5. *116th Congress Public Law 122 Protecting America's Food and Agriculture Act of 2019* (U.S. Government Publishing Office, 2020); https://www.congress.gov/116/plaws/publ122/PLAW-116publ122.pdf
6. *U.S. Government Global Food Security Strategy Fiscal Year 2022–2026* (United States Agency for International Development, 2022); https://www.usaid.gov/sites/default/files/2022-05/Global-Food-Security-Strategy-FY22-26_508C.pdf
7. Karakoc, D. B., Konar, M., Puma, M. J. & Varshney, L. R. Structural chokepoints determine the resilience of agri-food supply chains in the United States. *Nat. Food* **4**, 607–615 (2023).
8. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2021).
9. Mehrabi, Z. World view. *Nature* **615**, 189 (2023).
10. Gbegbelegbe, S., Chung, U., Shiferaw, B., Msangi, S. & Tesfaye, K. Quantifying the impact of weather extremes on global food security: a spatial bio-economic approach. *Weather Clim. Extrem.* **4**, 96–108 (2014).
11. Brown, M. et al. *Climate Change, Global Food Security and the US Food System*. Munich Personal RePEc Archive (USDA, 2015); http://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf
12. Gaupp, F. Extreme events in a globalized food system. *One Earth* **2**, 518–521 (2020).
13. Chenarides, L., Manfredo, M. & Richards, T. J. COVID-19 and food supply chains. *Appl. Econ. Perspect. Policy* **43**, 270–279 (2021).
14. Mussell, A., Bilyea, T. & Hedley, D. Agri-food supply chains and COVID-19: balancing resilience and vulnerability. *Agri-Food Econ. Syst.* **519**, 1–6 (2020).
15. Davis, Z. S., Rager, C. B., Gac, F., Snow, J. & Reiner, P. *Strategic Latency Unleashed: The Role of Technology in a Revisionist Global Order and the Implications for Special Operations Forces*. Technical report (Lawrence Livermore National Lab, 2021).
16. Schneider, C. M., Moreira, A. A., Andrade, J. S., Havlin, S. & Herrmann, H. J. Mitigation of malicious attacks on networks. *Proc. Natl Acad. Sci. USA* **108**, 3838–3841 (2011).
17. Puma, M. J. Resilience of the global food system. *Nat. Sustain.* **2**, 260–261 (2019).
18. Gephart, J. A. & Pace, M. L. Structure and evolution of the global seafood trade network. *Environ. Res. Lett.* **10**, 125014 (2015).
19. Fair, K. R., Bauch, C. T. & Anand, M. Dynamics of the global wheat trade network and resilience to shocks. *Sci. Rep.* **7**, 7177 (2017).
20. Hummels, D. Transportation costs and international trade in the second era of globalization. *J. Econ. Perspect.* **21**, 131–154 (2007).
21. Kaluza, P., Kölzsch, A., Gastner, M. T. & Blasius, B. The complex network of global cargo ship movements. *J. R. Soc. Interface* **7**, 1093–1103 (2010).

22. Karakoc, D. B. & Konar, M. A complex network framework for the efficiency and resilience trade-off in global food trade. *Environ. Res. Lett.* **16**, 105003 (2021).
23. Lin, X., Ruess, P. J., Marston, L. & Konar, M. Food flows between counties in the United States. *Environ. Res. Lett.* **14**, 084011 (2019).
24. Karakoc, D. B., Wang, J. & Konar, M. Food flows between counties in the United States from 2007 to 2017. *Environ. Res. Lett.* **17**, 034035 (2022).
25. Smith, T. M. et al. Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains. *Proc. Natl Acad. Sci. USA* **114**, E7891–E7899 (2017).
26. *Grain Transportation Report*. Technical report, Agricultural Marketing Service (U.S. Department of Agriculture, 2022).
27. *National Freight Strategic Plan Full Report*. Technical report, Bureau of Transportation Statistics (U.S. Department of Transportation, 2020).
28. Rock Island District. *Inland Waterway Navigation Value to the Nation*. Technical report (U.S. Army Corps of Engineers, 2004).
29. *Cartographic Boundary Shapefiles* (United States Census Bureau, 2021); https://www.census.gov/geographies/mapping-files/2016/geo/carto-boundary-file.html
30. *Freight Analysis Framework Version 5 (FAF5)* (Oak Ridge National Laboratory, 2020); https://faf.ornl.gov/faf5/dtt_domestic.aspx
31. Denicoff, M. R., Prater, M. & Bahizi, P. *Soybean Transportation Profile*. Technical report, Agricultural Marketing Service (U.S. Department of Agriculture, 2014).
32. Valdes, C., Gillespie, J. & Dohlman, E. *Soybean Production, Marketing Costs, and Export Competitiveness in Brazil and the United States*. Economic Research Service (US Department of Agriculture, 2023).
33. Prokopy, L. S. et al. Useful to usable: developing usable climate science for agriculture. *Clim. Risk Manag.* **15**, 1–7 (2017).
34. Karakoc, D. B. & Konar, M. Optimization of national grain imports to balance risk and return: a portfolio theory approach. *Environ. Res. Food Syst.* **1**, 011001 (2024).
35. Agricultural Marketing Service. *USDA Agri-Food Supply Chain Assessment: Program and Policy Options for Strengthening Resilience*. Technical report (U.S. Department of Agriculture, 2022).
36. *Food Defense Guidelines for the Transportation and Distribution of Meat, Poultry, and Processed Egg Products* (USDA Food Safety and Inspection Service, 2021); https://www.fsis.usda.gov/sites/default/files/media_file/2020-07/Transportation_Security_Guidelines.pdf
37. Mbow, C. et al. *Food Security*. Technical report (IPCC, 2020).
38. Food System Transformation Framework. *USDA* https://www.usda.gov/media/press-releases/2022/06/01/usda-announces-framework-shoring-food-supply-chain-and-transforming (2022).
39. *Freight Railroads & Climate Change: Reducing Emissions, Enhancing Resiliency* (Association of American Railroads, 2023); https://www.aar.org/wp-content/uploads/2023/06/AAR-Climate-Change-2023-Report.pdf
40. Li, M. et al. Global food-miles account for nearly 20% of total food-systems emissions. *Nat. Food* **3**, 445–453 (2022).
41. Weber, C. L. & Matthews, H. S. Food-miles and the relative climate impacts of food choices in the United States. *Environ. Sci. Technol.* **42**, 3508–3513 (2008).
42. Foong, A., Pradhan, P., Frör, O. & Kropp, J. P. Adjusting agricultural emissions for trade matters for climate change mitigation. *Nat. Commun.* **13**, 3024 (2022).
43. Wang, J., Karakoc, D. B. & Konar, M. The carbon footprint of cold chain food flows in the United States. *Environ. Res. Infrastruct. Sustain.* **2**, 021002 (2022).
44. Andrew, R. M. A comparison of estimates of global carbon dioxide emissions from fossil carbon sources. *Earth Syst. Sci. Data* **12**, 1437–1465 (2020).
45. *National Transportation Atlas Database: 2015* (Bureau of Transportation Statistics United States Department of Transportation, 2023); https://doi.org/10.21949/1502428
46. *Freight Facts and Figures* (U.S. Department of Transportation, 2020); https://data.bts.gov/stories/s/Freight-Transportation-System-Extent-Use/r3vy-npqd#top-25-water-ports-by-tonna
47. Ballou, R. *Business Logistics Management* (Prentice Hall, 1998).
48. Dong, J. et al. *Modeling Multimodal Freight Transportation Network Performance Under Disruptions*. Technical report, Iowa State University (Center for Transportation Research and Education, 2015).
49. Kharrazi, A., Yu, Y., Jacob, A., Vora, N. & Fath, B. D. Redundancy, diversity, and modularity in network resilience: applications for international trade and implications for public policy. *Curr. Res. Environ. Sustain.* **2**, 100006 (2020).
50. Ulanowicz, R. E. Quantifying sustainable balance in ecosystem configurations. *Curr. Res. Environ. Sustain.* **1**, 1–6 (2020).
51. Spellerberg, I. F. & Fedor, P. J. A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the, 'Shannon–Wiener' Index. *Glob. Ecol. Biogeogr.* **12**, 177–179 (2003).
52. Kruse, C. J. et al. *A Modal Comparison of Domestic Freight Transportation Effects on the General Public: 2001–2019* (Texas A&M Transportation Institute, 2021).
53. SCTG Commodity Code List. *U.S. Census Bureau* https://bhs.econ.census.gov/bhsphpext/brdsearch/scs_code.html (2023).

Acknowledgements

This work is based upon work supported by the National Science Foundation grant numbers CBET-1844773 ('CAREER: A National Strategy for a Resilient Food Supply Chain'), DEB-1924309 ('CNH2-L: Feedbacks between Urban Food Security and Rural Agricultural Systems'), BCS-2032065 ('RAPID: Spatial Resilience of Food Production, Supply Chains, and Security to COVID-19') and CBET-2115405 ('SRS RN: Multiscale RECIPES (Resilient, Equitable, and Circular Innovations with Partnership and Education Synergies) for Sustainable Food Systems'). This research was also supported by the US Department of Agriculture ('Building resilience to shocks and disruptions: Creating sustainable and equitable local and regional food systems in the US Midwest region and beyond'; grant number 2023-68012-39076). Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s).

Author contributions

D.B.K. and M.K. conceptualized the project. D.B.K. and M.K. developed the methodology. D.B.K. curated the data, conducted the formal analysis and investigation, and generated the data visualizations. D.B.K. and M.K. wrote the original draft of the paper and edited it according to reviewer comments. M.K. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-025-01128-9.

Correspondence and requests for materials should be addressed to Megan Konar.

Peer review information *Nature Food* thanks Catherine Brinkley, Kilian Kuhla and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

nature portfolio

Corresponding author(s): Megan Konar

Last updated by author(s): 01/16/2025

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a | Confirmed

☒ ☐ The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement

☒ ☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly

☒ ☐ The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.

☒ ☐ A description of all covariates tested

☒ ☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons

☒ ☐ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)

☒ ☐ For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted
Give P values as exact values whenever suitable.

☒ ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings

☒ ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes

☒ ☐ Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	The custom code is developed for reading and analyzing the publicly available Freight Analysis Framework (FAF) data and National Transportation Atlas Dataset (NTAD) shapefiles. The custom code is developed in both RStudio version 4.0.2 and QGIS version 3.28.2, which is available upon request.
Data analysis	The custom code is developed for (i) mapping the FAF-level agri-food flow networks data onto real-world highway, railway, and waterway layouts, and (ii) investigating the trade-off between sustainability, efficiency, and resilience of agri-food transit across modes. The custom code is developed in RStudio version 4.0.2 and QGIS version 3.28.2, which is available upon request.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The Freight Analysis Framework (FAF) data for the year 2017 that supports the findings of this study are available in Oak Ridge National Laboratory, https://faf.ornl.gov/faf5/. The National Transportation Atlas Database (NTAD) shapefiles of the national highways, railways, and waterways for the year 2015 that supports the findings of this study are available in Bureau of Transportation Statistics, https://doi.org/10.21949/1502428.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	The study does not contain human research participants.
Population characteristics	The study does not contain human research participants.
Recruitment	The study does not contain human research participants.
Ethics oversight	The study does not contain human research participants.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The empirical agri-food movement at Freight Analysis Framework spatial scale across the nation's highways, railways, and waterways are mapped onto the real-world transportation infrastructure layouts. Further, the trade-off between sustainability (total carbon dioxide emission of transit), efficiency (total cost of transit), and resilience (adaptability to reroute in case of disruptions) is assessed across the agri-food transportation modes.
Research sample	Empirical data consists of the bilateral (i.e., in and out) food flow information between Freight Analysis Framework (FAF) within the United States for both single commodities individually and aggregated commodities together. The data is collected for the year 2017. The food flow information is available in net amount (weight), and they are separated by 7 SCTG (Standard Classification of Transported Goods) codes.
Sampling strategy	From the existing dataset, food flows between Freight Analysis Framework (FAF) zones are analyzed for higher granularity. The study year is chosen as 2017 since it is the most up-to-date available data. From aggregated commodity groups, all agri-food commodity flows is analyzed. For separate food commodity networks, 7 separate SCTG (Standard Classification of Transported Goods) codes are analyzed. These are SCTG 01: live animals and fish, SCTG 02: cereal grains, SCTG 03: agricultural products, SCTG 04: animal feed, SCTG 05: meat and their preparations, SCTG 06: milled grains, and lastly SCTG 07: other prepared foodstuff. The commodity groups also shaped the data availability.
Data collection	The empirical data for Freight Analysis Framework (FAF) scale food flows is obtained from Oak Ridge Laboratory. Oak Ridge Laboratory integrates data from various sources to create a comprehensive picture of freight movement among states and major metropolitan areas by all modes of transportation and Commodity Flow Survey data serves as the backbone. The real-world infrastructure layout of the national highways, railways, and waterways are adopted from the publicly available data from the National Transportation Atlas Database.
Timing and spatial scale	The food flow networks in the year 2017 within the continental United States is analyzed in this study, as it is the most up-to-date data available. The analyzed food flow networks are in Freight Analysis Framework (FAF) scale within the United States. Freight Analysis Framework (FAF) zones divide states within the United States generally into two separate areas, more rural vs urban/metropolitan areas. Therefore, FAF data provides more detail and higher granularity than food flows between states within the United States. The backbone of Freight Analysis Framework (FAF) data is the Commodity Flow Survey (CFS) data which is collected

	and published once every 5 years (years ending with '2' and '7'). The highway, railway, and waterway infrastructure layout within the continental United States is for the year 2015, as it is the most up-to-date available data. The National Transportation Atlas Database (NTAD) data provides the shapefile of each transportation mode individually.
Data exclusions	The study is restricted to the Continental United States (i.e., CONUS), so data regarding the food flows within the Freight Analysis Framework (FAF) zones in Alaska and Hawaii are excluded from this study. These locations are excluded as they have different transportation infrastructure properties than the rest of the study area, hence they are treated as outliers.
Reproducibility	The custom code based study is reproducible as it can be implemented on different datasets.
Randomization	Randomization is not relevant to the study as statistical tests are not implemented on the existing datasets.
Blinding	Blinding is not relevant to the study as statistical tests are not implemented on the existing dataset.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging