

# Multimodal and Multicereal Grain Transportation Patterns in the United States Across Cost, Emission, and Adaptability Optimization Scenarios

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**ABSTRACT:** Cereal grains are staple foods in the daily diets of millions of Americans, given their affordability and availability. However, transportation of these commodities between domestic supply and demand locations has a significant environmental impact, as it often involves long distances, large quantities, and diesel trucks. Fortunately, their dry and nonperishable nature allows decision-makers to redesign their nationwide bulk transit to lower carbon dioxide emissions without compromising the ability to reroute in case of disruptions. Here, we adopt a data-driven multiobjective optimization model to compare empirical multimodal and multicereal grain transit patterns in the United States with cost, emission, and adaptability optimization scenarios. We uncover that actual patterns are highly adaptable, yet by strategically allocating cereal grains across highways, railways, and waterways, transportation scenarios with reduced carbon emissions are possible. Our findings can inform efforts to balance efficiency, resilience, and sustainability in agri-food transportation.

**KEYWORDS:** cereal grain transit patterns, sustainability, resilience, cost



## INTRODUCTION

A well-functioning agriculture and food supply chain within the United States is crucial for economic stability and national security.<sup>1</sup> In particular, cereal grains (e.g., corn, rice, and wheat) are essential goods for the daily diets of millions<sup>2</sup> for which the U.S. has a strategic advantage.<sup>3</sup> The U.S. is the net producer of cereal grains, and these commodities move in large quantities along large-scale, multimodal transportation infrastructures. The complex transportation system consists of highways, railways, and waterways, and they connect production, processing, and consumption locations that stretch nationwide.<sup>4</sup> Inland waterways move the majority of the cereal grain on the Mississippi River<sup>5</sup> whereas transportation by rail takes place on a well-integrated national network.<sup>6</sup> Highways carry multigrains along both intercity and long-distance hauls.<sup>7</sup>

Highways, railways, and waterways are the backbone of national agri-food supply chains.<sup>8</sup> They directly influence the availability and affordability of food.<sup>9</sup> Therefore, it is crucial to evaluate resilience, efficiency, and sustainability of the distribution of agri-food commodities along these transportation infrastructures.<sup>10</sup> To date, research has individually addressed these goals. For instance, opportunities to enhance the resilience of agri-food transit against various disruptions, e.g., pathogen outbreaks<sup>11</sup> pandemics,<sup>12</sup> and infrastructure disruptions<sup>13</sup> have been put forward. Improvements to the efficiency of agri-food transportation systems, in terms of energy<sup>14</sup> and cost,<sup>15,16</sup> have also been considered. Sustainability concerns have been a more recent focal area of research within agri-food transportation.<sup>17–19</sup> Even though emissions from transport represent a relatively small portion of the total

carbon footprint of agri-food systems, food transit in the U.S. emits over 100 million tons of carbon dioxide annually<sup>21</sup> making it important to consider.<sup>20,22</sup> Further, what is still missing in the literature is uncovering the U.S. multigrain transit patterns on real-world infrastructure and evaluating how they compare to optimized resilience-efficiency-sustainability goals collectively.<sup>23</sup> Such a study will improve our understanding of agri-food systems that are essential for the national economy and food security and fill an important research gap.

In this study, we adopt a multiobjective optimization model to study the multicereal grain transit across real-world highways, railways, and waterways within the U.S. We first assess the relationship between efficiency, resilience, and sustainability in multicommodity and multimodal cereal grain transit and then evaluate how existing patterns compare across optimization scenarios to highlight realistic future improvements. Here, we define the total cost of transit as efficiency, total carbon dioxide emissions as sustainability, and supply-demand-balanced transit rerouting adaptability as resilience. The research questions that guide this study are: (1) What is the relationship between cost and adaptability in multicommodity and multimodal cereal grain transit? (2) What is

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**Table 1. List of Individual Cereal Grains Included in SCTG 02<sup>a</sup>**

Cereal Grain Type	Corn	Barley	Rye	Sorghum	Wheat	Oats	Rice
SCTG 02 contribution	87%	0.67%	0.08%	2%	8.7%	0.17%	1.45%

<sup>a</sup>Their percentage contribution to the national cereal grain production in mass is also listed. The national average is similar to the per-state production trends. In this study, we break down the total SCTG 02 supply to individual cereal grains by multiplying it with per-state contributions.



**Figure 1.** Real-world shortest path layouts between 129 FAF zones along the (A) highways, (B) railways, and (C) waterways within the U.S. Red points indicate the geographic centroid of each FAF zone. We convert the mode-specific infrastructure shapefiles into a graph of 129 nodes and  $129 \times 128$  shortest paths to be included in our multiobjective optimization model.

the relationship between emission and adaptability in multi-commodity and multimodal cereal grain transit? (3) How does actual multicommodity and multimodal cereal grain transit resemble different optimization scenarios?

Our study is shaped by the data-driven and application-heavy nature of the above research questions that we aim to address. Our contribution to the literature involves deriving policy implications for real-world U.S. cereal grain transportation by leveraging existing geographic information science and operations research methods. Yet, our methods also include novel contributions such as: the computation of real-world distances and path layouts along the nation's highways, railways, and waterways; conceptual design of a supply–demand-balanced transit rerouting adaptability metric and formulating its linear approximation; and integration of both the new metric and path information into multiobjective optimization models. Thus, in addition to the discovery of U.S. cereal grain transportation patterns, our work highlights the flexibility of existing transportation planning methods and inspires novel applications for critical supply chains.

## METHODS

Here, we explain our input data, cost-emission-adaptability metrics, and multiobjective optimization model formulation. We also highlight the novel contributions of our methods, which include computation of real-world transportation infrastructure distances and path layouts, design of an adaptability metric, and integration of this new information into existing optimization models. Please note that our study is restricted to the continental United States (e.g., CONUS), so Alaska and Hawaii are not included<sup>24</sup> and our goal is to provide insights for better-informed decision-making for U.S. cereal grain transit (please refer to [Supporting Information](#) for a more detailed explanation of our methodology).

**Multicereal Grain Transit Data.** We collect the most up-to-date Freight Analysis Framework (FAF) data for the transit of cereal grains [in mass] within the United States for 2022. FAF was created through a partnership between the U.S. Bureau of Transportation Statistics and the Federal Highway Administration to provide information on U.S. freight movements.<sup>25</sup> FAF divides the U.S. states into their more urban vs rural areas, providing a total of 129 FAF zones within the CONUS.<sup>25</sup> The cereal grain commodities we study are recorded by the Standard Classification of Transported Goods (SCTG) 02<sup>26</sup> and listed in [Table 1](#). Please note that

“soybeans” are not included within the SCTG 02 classification by the U.S. Census Bureau definition.

From the 2022 FAF data, we individually collect cereal grain transit only between domestic supply and demand locations along highways, railways, and waterways. Thus, the import and export of cereal grains are outside the scope of our analysis. For each transportation mode, we quantify per state the outflows (e.g., supplies) of corn, barley, rye, sorghum, wheat, oats, and rice. To do so, we calculate the percentage contribution of each individual cereal grain's production within the total cereal grain production per state.<sup>27</sup> These percentages are then multiplied by the origin-specific link-level cereal grain outflows. For instance, 80.73% of all cereal grain production in Alabama is “corn.” Thus, we break down and define 80.73% of all outflows from Alabama FAF zones as “corn outflows”.

### Multimodal Transportation Infrastructure Networks.

We use the shapefiles of CONUS highways, railways, and waterways from the National Transportation Atlas Database (NTAD) to compute the real-world mode-specific distances and path layouts between the CONUS FAF zones. The 2015 NTAD, the most up-to-date, is a nationwide geographic data set of transportation infrastructure that is developed by the U.S. Department of Transportation, Bureau of Transportation Statistics (BTS).<sup>28</sup> We limit our NTAD data to (i) interstate and state highways, (ii) Class I–II–III rail lines, and (iii) inland waterways to be consistent with the freight reports of BTS (please refer to [Supporting Information](#) for the illustration of these infrastructure layouts spatially located by FAF zones with their geographical centroids).

To compute mode-specific real-world distances and path layouts between CONUS FAF zones, we develop a novel crosswalk between QGIS and RStudio. In our crosswalk, each geocoded vector line is converted into a network link, and for the entirety of a connected link, its start and end points are assigned with a network node. Among these geocoded network nodes, we subset the ones that are located closest to each FAF zone's geographic centroid. Thus, each FAF zone is represented by a single network node, and each infrastructure shapefile is subsized into a spatial graph of 129 nodes. Along these spatial graphs, by using Dijkstra's algorithm,<sup>29</sup> we construct the mode-specific shortest paths between every origin and destination FAF zone pair with their real-world distances [miles], as seen in [Figure 1](#) for the first time in the literature (please refer to [Supporting Information](#) for a more detailed explanation of our data assumptions, network statistics, and novel QGIS-RStudio crosswalk).

**Cost, Emission, and Adaptability Metrics.** To quantify the total cost, emission, and adaptability specifically for the transit of each cereal grain commodity per mode, we used the information captured in our spatially located transportation infrastructure networks. The mode- and commodity-specific total cost of transit,  $C^{mk}$ , is formulated as in eq 1 where  $m$  is the transportation mode,  $k$  is the individual cereal grain commodity,  $W$  is the mass movement [tons], and  $D$  is the real-world distance [miles] between each FAF zone origin  $i$  and destination  $j$  pair. Finally,  $c$  is the unit cost of transit per ton-mile specific to each mode for the year 2014 that is adopted from the literature.<sup>30</sup> Higher values of  $C^{mk}$  indicate more costly cereal grain transit.

$$C^{mk} = \sum_{ij} W_{ij}^{mk} \times D_{ij}^{mk} \times c^m \quad (1)$$

We quantify the total carbon emissions associated with individual cereal grain transits for each transportation mode in a similar way. Total carbon emissions of transit for each cereal grain and mode,  $E^{mk}$ , are formulated in eq 2 (similar to the total transit cost calculations in eq 1). Now,  $e^m$  is the CO<sub>2</sub> emission coefficient per unit ton-mile specific to each mode, and it is collected from the literature.<sup>31</sup> Higher values of  $E^{mk}$  indicate more carbon emissions [tons of CO<sub>2</sub>] during cereal grain transit.

$$E^{mk} = \sum_{ij} W_{ij}^{mk} \times D_{ij}^{mk} \times e^m \quad (2)$$

Here, we introduce a novel adaptability metric that is developed specifically for the multimodal transit of multicereal grains within the U.S. Our new adaptability metric is inspired by the Shannon diversity index,<sup>32</sup> Herfindahl-Hirschman index,<sup>33</sup> and network path redundancy measure<sup>34</sup> to quantify resilience. As such, it rewards transit that utilizes multiple alternative routes with an even load distribution between origins and destinations. Such systems will still facilitate a supply-demand balanced cereal grain transit along many existing routes in case of disruptions; thus, they are considered more resilient (please refer to Supporting Information for a more detailed explanation of our adaptability metric).

In our adaptability metric, we first quantify the evenness of load distribution along the existing routes by the range of mass flow,  $R^{mk}$ . Then, we compute the average number of alternative routes,  $N^m$ . Here, a lower range of mass flow indicates a more even cereal grain load distribution, whereas a higher number of alternative paths between FAF zones indicates a continuing transit even if one of the paths is blocked. Thus, we formulate our adaptability metric  $A^{mk}$  as seen in eq 3 where lower values state more resilient multimodal transit of multicereal grains within the U.S. (please refer to Supporting Information for the comparison of our adaptability metric vs Shannon diversity index, Herfindahl-Hirschman index, and network path redundancy measure).

$$A^{mk} = R^{mk} / N^m \quad (3)$$

We list the unit cost of transit, unit carbon dioxide emission, and average number of alternative paths for each transportation mode in Table 2. We further discuss how the foundational nature of each transportation infrastructure drives the adopted and computed measures of cost-emission-adaptability in Supporting Information.

**Table 2. Cost, Emission, and Adaptability Metrics per Transportation Mode<sup>a</sup>**

Mode	Unit cost per ton-mile	Unit CO <sub>2</sub> emission per ton-mile	Average number of alternative paths
Highways	\$3.88	140.70 gr	1.68
Railways	€5.0	21.57 gr	1.16
Waterways	€1.6	15.08 gr	0.56

<sup>a</sup>Mode-specific unit cost of transit [cents per ton-mile] and unit CO<sub>2</sub> emission [grams per ton-mile] are adopted from the literature. We compute the average number of alternative paths per mode by the node connectivity algorithm.

**Multiobjective Optimization Model.** We adopt a multiobjective optimization model that is specifically formulated for multimodal transit of multicereal grains in the U.S. The multiple objectives we have for such a system are minimizing the total cost, as seen in eq 4, minimizing the total CO<sub>2</sub> emission as seen in eq 5, and maximizing the transit adaptability, as seen in eq 6. Along with our model in eqs 4–10,  $i$  and  $j$  represent 129 FAF zone origins and destinations, respectively,  $m$  represents 3 transit modes, and  $k$  represents 7 cereal grain commodities.  $S_i^{mk}$  is the total mass supply per commodity-mode-FAF zone origin, whereas  $B_j^{mk}$  is the total mass demand per commodity-mode-FAF zone destination.

$$\min \sum_m \sum_k \left( C^{mk} = \sum_i \sum_j W_{ij}^{mk} \times D_{ij}^{mk} \times c^m \right) \quad (4)$$

$$\min \sum_m \sum_k \left( E^{mk} = \sum_i \sum_j W_{ij}^{mk} \times D_{ij}^{mk} \times e^m \right) \quad (5)$$

$$\min \sum_m \sum_k (A^{mk} = R^{mk} / N^m) \quad (6)$$

$$\text{s.t.} \sum_m \sum_j W_{ij}^{mk} \leq \sum_m S_i^{mk} \quad \forall i, k \quad (7)$$

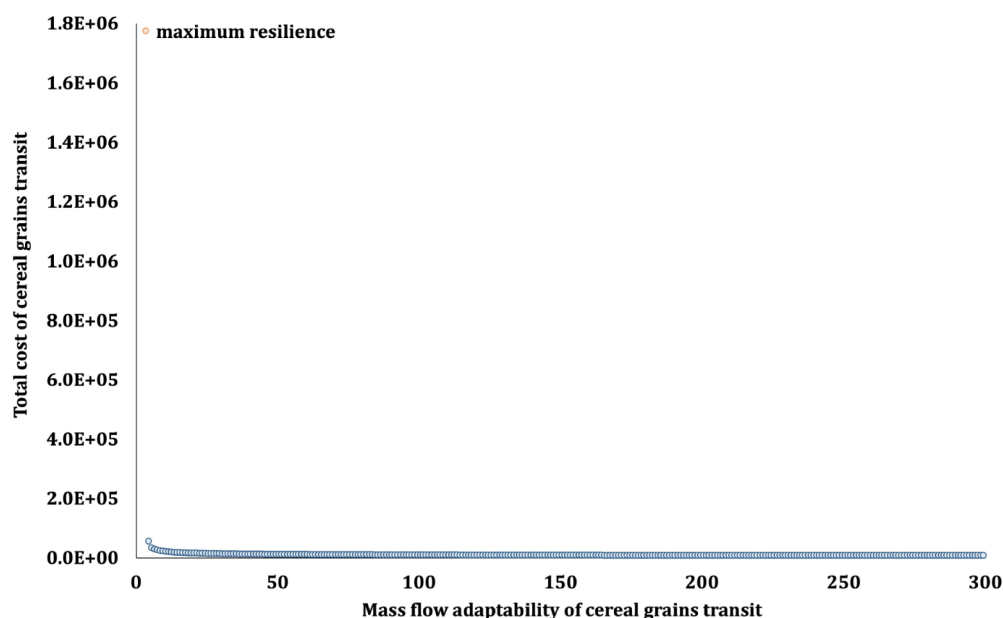
$$\sum_m \sum_i W_{ij}^{mk} \geq \sum_m B_j^{mk} \quad \forall j, k \quad (8)$$

$$R^{mk} = \max(W_{ij}^{mk}) - \min(W_{ij}^{mk}) \quad \forall m, k \quad (9)$$

$$W_{ij}^{mk} \geq 0 \quad \forall i, j, m, k \quad (10)$$

Constraints in our model are also formulated according to the nature of our system. In eqs 7 and 8, we allow complete mode switching during the transit between any FAF origin and destination, as all cereal grain commodities are dry and nonperishable. These two constraints also ensure a per-commodity mass balance, where the total outflow from each FAF origin cannot exceed its supply capacity and the total inflow to each FAF destination should at least meet its demand. Equation 9 defines the mass movement range per commodity and mode as part of our adaptability metric, and eq 10 determines that cereal grain commodity  $k$  mass load on mode  $m$  between FAF zones  $i$  and  $j$  should be greater than or equal to 0.

Due to data limitations within our system, we do not consider capacity restrictions on mode-specific paths. Thus, our model can allocate cereal grain mass to each path as flexibly as it can. In practice, there may be stricter constraints



**Figure 2.** Pareto-optimal frontiers represent the trade-off between the cost and adaptability of multicommodity cereal grain transit within the U.S. Higher values on the  $y$ -axis represent higher total cost of transit, whereas higher values on the  $x$ -axis represent lower adaptability of transit.  $x$ -axis values are within the range of [3.43, 299.31] and are determined by the  $\epsilon$ -constraint approach, where 3.43 is the best-case scenario for adaptability and 299.31 is the adaptability value achieved under the minimum cost scenario.

on the number of fleet vehicles or traffic congestion within paths. However, here we enforce capacity restrictions through individual grain supplies per FAF zone.

We solve our multiobjective optimization model with the  $\epsilon$ -constraint approach<sup>35</sup> to uncover the relationship between cost, emission, and adaptability of multimodal transit of multicereal grains within the U.S. To accomplish this, we convert maximizing adaptability (eq 6) into an  $\epsilon$ -constraint as seen in eq 11 and keep minimizing total cost (eq 4) and minimizing total emission (eq 5) as the single objective function, respectively, in individual runs.

$$\sum_m \sum_k A^{mk} \leq \epsilon \quad (11)$$

To determine the  $\epsilon$  values in eq 11, we first solve our model with a single objective function of minimizing the total cost (eq 4). Then, we compute the adaptability of the achieved optimum system, which is adopted as the upper limit of  $\epsilon$ . The lower limit of  $\epsilon$  is obtained by the optimum solution of our model that has maximizing adaptability (eq 6) as its single objective function. At each run, we decrease the  $\epsilon$  value by 1 (until the lower limit value) to tighten our adaptability constraint. This approach forces our model to change cereal grain mass allocation along the transit paths to achieve better adaptability (lower metric values) at every run. We follow the same procedure for minimizing the total emission (eq 5).

## RESULTS AND DISCUSSION

In this section, we present the uncovered relationship between cost, emission, and adaptability in multimodal and multicereal grain transit within the U.S., as well as comparison of its actual patterns with optimization scenarios. Further, we discuss the policy implications of our findings.

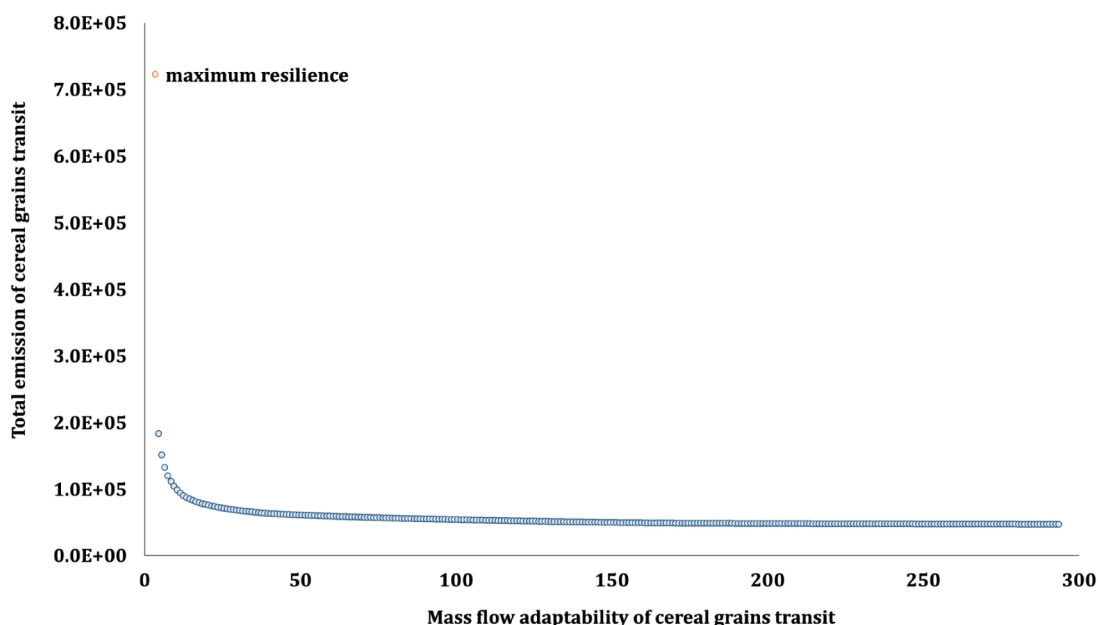
**Cost vs Adaptability in Multimodal Multicereal Grain Transit.** We investigate the relationship between cost and adaptability in multimodal and multicereal grain transit at the

FAF scale. To do so, we first solve our optimization model with only the objective of eq 4, minimizing the total cost. By focusing solely on minimizing the total cost of transit, the unit cost parameter per mode determines the optimal solution for the model without violating any supply and demand constraints (eqs 7 and 8). Given that the unit transit cost is €1.6 for waterways and €5.0 for railways per ton-mile, as shown in Table 2, the optimum solution of our cost minimization model aims to assign all cereal grain distribution to waterways.

However, not all FAF zones have ports or docks—nor do they have access to inland waterways. Thus, to meet the demand of such FAF zones, the model chooses to transport goods through railways. In the end, the optimum solution assigns 70.56% and 29.44% of total cereal grain mass transit to railways and waterways, respectively. In this case, the total cost of transport becomes 9.71E+3 million dollars, where 8.35E+3 million dollars is accounted for by the railways and 1.36E+3 million dollars is accounted for by the waterways.

We then solve our optimization model only with the objective of eq 6, maximizing the adaptability. In this case, our optimization model allocates the cereal grain mass onto the highway routes as equally as possible, since they can connect every FAF zone to each other through multiple alternative paths. Instead of continuing to allocate more mass on highways and disrupting the evenness of load distribution, our model then moves on to allocating mass equally to railway paths until all the FAF zone-specific demands are met. In the end, this optimum solution showcases almost 100% of the cereal grain transit along the highways, which, however, accounts for 3.34E+6 million dollars in total cost.

These completely opposite cereal grain load assignments on modes uncover the trade-off between cost and adaptability goals of transit, where the most adaptable (e.g., resilient) mode of choice is highways, but the least costly (e.g., economically efficient) mode of choice is waterways for the U.S. multicereal grain supply chain. Figure 2 shows the Pareto-optimal frontiers that we achieve through the  $\epsilon$ -constraint approach to further



**Figure 3.** Pareto-optimal solutions represent the trade-off between CO<sub>2</sub> emission and adaptability of multicereal grain transit within the U.S. Higher values on the y-axis represent higher total carbon emissions of transportation, whereas higher values on the x-axis represent lower adaptability of transportation. x-axis values are within the range of [3.43, 294.25] and are determined by the  $\epsilon$ -constraint approach, where 3.43 is the best-case scenario for adaptability and 294.25 is the achieved adaptability under the most sustainable solution.

investigate this trade-off. There are 296 individual solutions that ensure the minimum total cost of transit under the set adaptability criterion. Based on the individual runs on our model, Pareto frontiers highlight that to achieve higher adaptability, more cereal grain transit should take place along the highways, which increases the total cost of transit as their per ton-mile unit cost of transit is \$3.88. On the other hand, more economically efficient cereal grain transit can be achieved by assigning load primarily to waterways and then to railways. However, this comes at the expense of cereal grain transit being more vulnerable to disruptions, as there are not many alternative paths that connect every FAF zone to each other along the waterways (e.g., the average number of nodes to remove to disconnect the network is 0.56, as seen in Table 2). Further, the load cannot be distributed evenly across the existing paths since the Mississippi riverbed contains the main canal and docks that facilitate more than 80% of all freight transit<sup>36</sup> and more than 60% of all agri-food transit.<sup>37</sup>

Our cost vs adaptability trade-off findings align with previous literature.<sup>38</sup> These results emphasize the existing competing relationship and the need to consider resilience (here, quantified through adaptability of transit) while designing agri-food supply chains, rather than solely focusing on economic efficiency.<sup>10</sup>

**Emission vs Adaptability in Multimodal Multicereal Grain Transit.** We investigate the relationship between carbon dioxide emissions and adaptability in multimodal and multicereal grain transportation using a similar approach as in section [Cost vs Adaptability in Multimodal Multicereal Grain Transit](#) where the optimization model tries to meet the demand of all FAF zones by distributing cereal grains along the waterways. Again, due to natural constraints, cereal grain transit between FAF zones that are not reachable via waterways is then facilitated through railways.

The optimum solution under objective of eq 5, minimizing CO<sub>2</sub> emissions, assigns 0% of the cereal grains to highways, as

this mode has the highest unit carbon emission per ton-mile, 140.70 gr CO<sub>2</sub> (see Table 2). Instead, our model allocates 76.35% and 23.65% of the total cereal grain mass to railways and waterways, respectively. As seen in Table 2, railways emit 1.43 times more CO<sub>2</sub> than waterways. However, the unit cost of railways is 3.13 times that of waterways. So, the most sustainable solution emphasizes railways more compared to the most cost efficient solution.

Given the optimum solution for maximizing the adaptability (see [Cost vs Adaptability in Multimodal Multicereal Grain Transit](#)), we again observe a completely opposite cereal grain load assignment on modes between sustainability and adaptability goals of transit. Similar to [Cost vs Adaptability in Multimodal Multicereal Grain Transit](#), the emission vs adaptability trade-off becomes clear as highways are the most adaptable (e.g., resilient) mode, but waterways are the most sustainable (e.g., least CO<sub>2</sub> emission) mode for the U.S. multicereal grain supply chain. Figure 3 illustrates 274 Pareto-optimal frontiers that ensure the minimum CO<sub>2</sub> emission under each adaptability criterion. To achieve higher sustainability, more cereal grain transit should take place through waterways and railways. However, these two transportation modes are approximated to have fewer alternative paths than highways. Thus, in the case of a disruption in one of the paths, particularly along the major mass-carrying ones, rerouting the transit will be harder, which will cause a larger supply and demand imbalance. On the contrary, more adaptable cereal grain transit takes place along the highways, as they are the most resilient mode (e.g., easiest to reroute with a more even load distribution), but this comes at the expense of highest emissions.

We summarize the total cost, emissions, and adaptability values for the minimum cost, maximum adaptability, and minimum emission scenarios across transportation modes in Table 3 to better summarize the uncovered trade-offs. Our findings are particularly important given the increased focus on

**Table 3. Total Cost, Emissions, and Adaptability Metric Values of Multi-Modal Transit of Multi-Cereal Grains Along the Nation's Highways, Railways, and Waterways Under Each Scenario<sup>a</sup>**

The most cost efficient scenario				
Mode	Cost [M \$]	Adaptability	CO <sub>2</sub> emission [Mtons]	Total mass allocation [tons]
Highways	0.00	0.00	0.00	0.00
Railways	8.35E+3	140.32	3.61E+4	7.72E+2
Waterways	1.35E+3	158.99	1.28E+4	3.22E+8
The most adaptable scenario				
Mode	Cost [M \$]	Adaptability	CO <sub>2</sub> emission [Mtons]	Total mass allocation [tons]
Highways	3.34E+6	3.43	1.21E+6	1.09E+9
Railways	4.88E−1	1.78E−5	2.11	8.89E+3
Waterways	0.00	0.00	0.00	0.00
The most sustainable scenario				
Mode	Cost [M \$]	Adaptability	CO <sub>2</sub> emission [Mtons]	Total mass allocation [tons]
Highways	0.00	0.00	0.00	0.00
Railways	9.56E+3	139.75	4.13E+4	8.35E+8
Waterways	7.01E+2	154.51	6.61E+3	2.59E+8

<sup>a</sup>Higher cost and emission values indicate less economically efficient and less sustainable transit scenarios, respectively. Lower adaptability values indicate distributing cereal grains more evenly across multiple alternative paths, thus resulting in more resilient values. 0 metric values indicate no mass allocation to that mode in the considered optimization scenario.

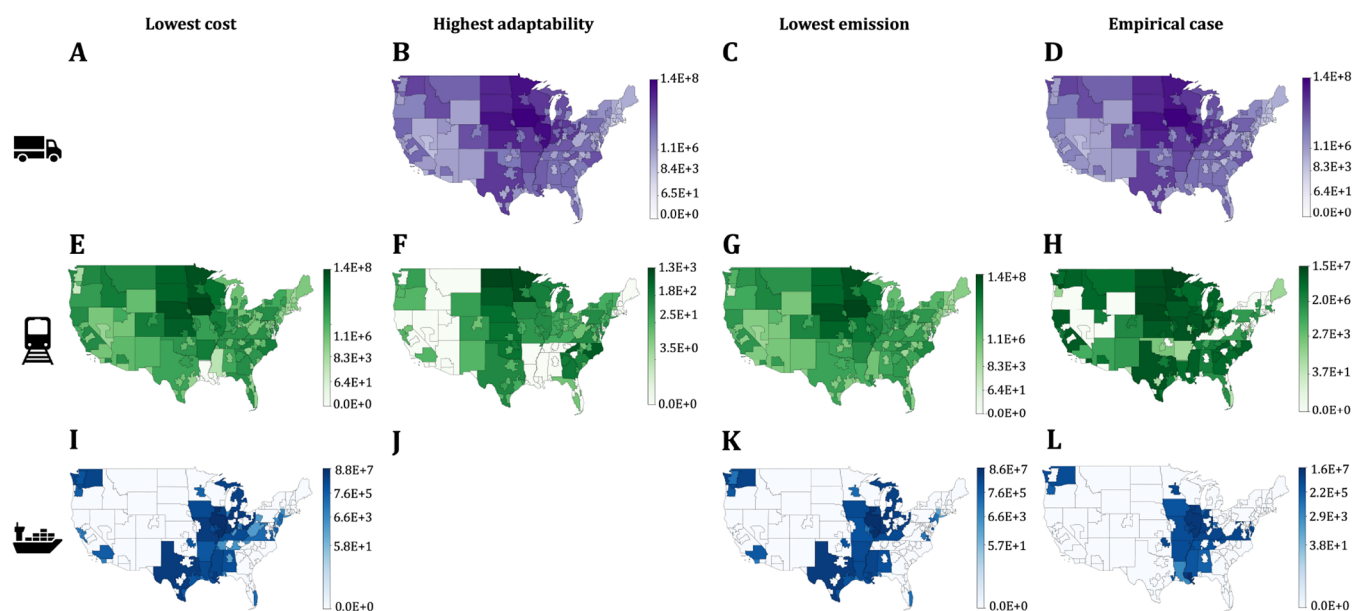
sustainability in agri-food supply chains in recent years.<sup>39</sup> Decision-makers may want to consider the potential loss of resilience (due to losing access to alternative routes with manageable supply-demand imbalance in the case of disruptions) that could arise from solely focusing on increasing sustainability (by reducing carbon emissions). Instead,

balancing solutions should be designed between these two goals.<sup>19</sup>

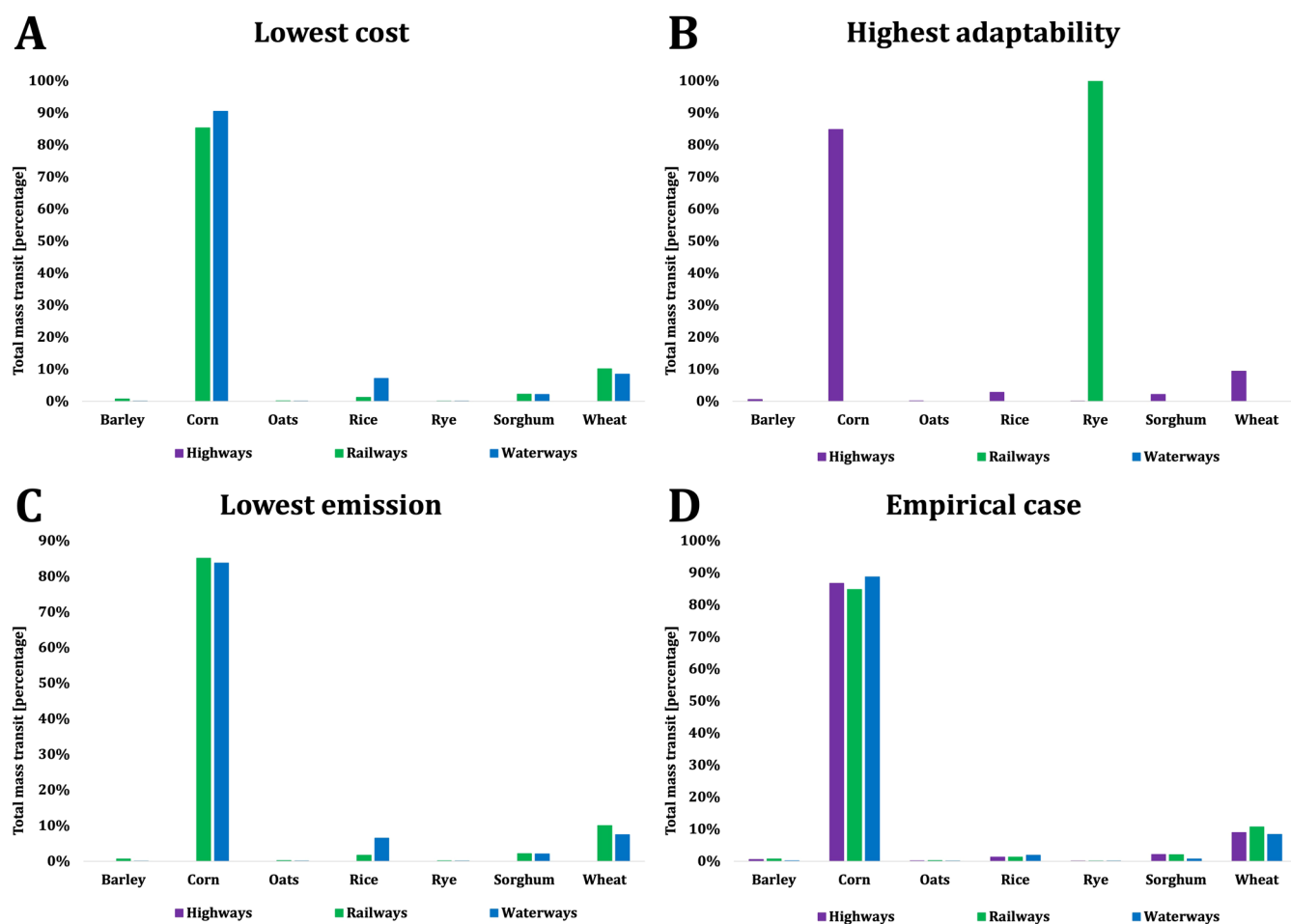
**Comparison of Actual Cereal Grain Transit to Optimization Scenarios.** Here, we evaluate how the actual multimodal multicereal grain transit patterns compare to optimization scenarios across FAF zones and commodities in detail. Figure 4 compares the total cereal grain transit mass for each FAF zone in the U.S. under cost, emission, and adaptability optimization scenarios. It also displays the cereal grain mass allocation per FAF zone in the real world based on the existing empirical data.

For each transportation mode, FAF zones in the Midwest carry the highest total cereal grain mass, which makes sense as the Midwest is the main producer of cereal grains.<sup>40</sup> Particularly, highways in Iowa, North Dakota, Illinois, Minnesota, and Nebraska carry the highest total cereal grain mass under the most adaptable transit scenario (Figure 4B). Similarly, railways in the Midwest generally carry the highest total cereal grain mass. Compared to highways, railways are utilized nationwide under each scenario. Total cereal grain mass is more heavily accumulated along the rail lines, except in the most adaptable scenario, which allocates 100% of load to highways due to the existence of more alternative paths to carry cereal grains. Lastly, waterways around the Mississippi River and Midwest FAF zones distribute the majority of the cereal grains in the most cost-efficient and sustainable scenarios, as well as the nationwide participation of inland waterways and major ports (such as Seattle, WA, Houston, TX, and Los Angeles, CA) is highlighted (Figure 4I,K).

Figure 4D–L highlights that the real-world empirical cereal grain transit across modes resonates with a combination of the most adaptable and least costly solution. We observe that the majority of the individual cereal grain commodities are distributed through highways in the empirical case where, similar to most adaptable scenario, mass is accumulated around the Midwest highway paths. However, there is considerably



**Figure 4.** Total mass [tons] transit of cereal grains broken down by each transportation mode under different scenarios. Cereal grain transit occurs in (A–D) highways, (E–H) railways, and (I–L) waterways. (A–E–I) represent the most cost-efficient scenario, (B–F–J) represent the most adaptable scenario, (C–G–K) represent the most sustainable scenario, and (D–H–L) represent the empirical case. Empty subplots indicate that there is no cereal grain mass allocation on the corresponding transportation mode in the optimum solution under each scenario.



**Figure 5.** Total mass [in percentage] transit along the nation’s highways, railways, and waterways across seven cereal grain commodities under different scenarios is presented. (A) The most cost-efficient cereal grain transit. (B) The most adaptable cereal grain transit. (C) The most sustainable cereal grain transit. (D) The empirical cereal grain transit occurred within the U.S. FAF zones.

**Table 4. Total Mass Allocation [percentage] of Individual Cereal Grain Commodities across Transportation Modes under the Most Cost-Efficient, Adaptable, and Sustainable Scenario as Well as the Empirical Case in 2022**

The most cost efficient scenario							
Mode	Barley	Corn	Oats	Rice	Rye	Sorghum	Wheat
Highways	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Railways	5.56E+6	6.59E+8	1.47E+6	9.73E+6	7.75E+5	1.72E+7	7.82E+7
Waterways	3.11E+5	2.69E+8	1.65E+5	2.13E+7	9.14E+4	6.30E+6	2.51E+7
The most adaptable scenario							
Mode	Barley	Corn	Oats	Rice	Rye	Sorghum	Wheat
Highways	5.87E+6	9.28E+8	1.64E+6	3.10E+7	8.58E+5	2.35E+7	1.03E+8
Railways	0.00	0.00	0.00	0.00	8.89E+3	0.00	0.00
Waterways	0.00	0.00	0.00	0.00	0.00	0.00	0.00
The most sustainable scenario							
Mode	Barley	Corn	Oats	Rice	Rye	Sorghum	Wheat
Highways	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Railways	5.64E+6	7.11E+8	1.50E+6	1.42E+7	7.90E+5	1.80E+7	8.40E+7
Waterways	2.29E+5	2.17E+8	1.32E+5	1.68E+7	7.63E+4	5.47E+6	1.93E+7
The empirical case							
Mode	Barley	Corn	Oats	Rice	Rye	Sorghum	Wheat
Highways	4.73E+6	7.80E+8	1.33E+6	1.21E+7	6.57E+5	1.90E+7	8.10E+7
Railways	1.04E+6	1.14E+8	2.67E+5	1.81E+6	1.04E+5	2.76E+6	1.45E+7
Waterways	6.59E+4	4.44E+7	2.33E+4	9.48E+5	3.27E+4	3.57E+5	4.20E+6

more railway and waterway usage in the empirical case compared to the most adaptable case, which shows spatial trends similar to those of the lowest-cost scenario. Thus, the empirical case seems to utilize all modes, even though priority is given to highways.

In addition, Figure 5 breaks down the percentage of mass transit on each transportation mode by individual cereal grain commodities under each scenario. It also compares the individual commodity mass transit between the empirical case and optimization scenarios. On average, 87% of the total cereal grain load is corn (see Table 1); therefore, the highest utilization of highways, railways, and waterways under each scenario is for corn transit. For the most cost-efficient and sustainable scenarios, corn transit through railways is very similar, e.g., 6.59E+8 and 7.11E+8 tons, respectively (see Table 4). However, for the most cost-efficient scenario, almost 20% more corn (2.69E+8 tons, as seen in Table 4) is distributed through waterways compared to the most sustainable scenario (2.17E+8 tons, as seen in Table 4). For the most adaptable scenario, all the corn transit is shifted to highways (Figure 5B) as, from Midwest to every other FAF zone, there exist multiple paths along the highways and they carry equal loads of corn [in tons]. In addition to corn, wheat is another commodity that experiences mode shifts to achieve better total cost, emission, and adaptability during transit. Wheat transit follows similar trends with corn, with similar amounts are distributed along railways for the most cost-efficient and most sustainable scenarios. However, 25% more wheat is allocated to waterways for the most sustainable transit scenario compared with the most cost-efficient design (see Table 4). Due to relatively smaller contribution of other individual cereal grains to total production, their mode shifts under different scenarios do not influence the overall cost, emission, and adaptability concerns as much.

Similarly, in Figure 5D, we observe that majority of the individual cereal grain commodities are distributed through highways in the empirical data. In fact, the real-world data for corn and wheat on the highways are only 15% and 21% less, respectively, than in the most adaptable optimum solution (as seen in Table 4). This indicates that actual multimodal multicereal grain transit patterns most closely map to our adaptability optimization, rather than the cost and emissions scenarios, indicating that having the flexibility and accessibility of alternative paths is a major objective.

Such observations in Figures 4 and 5 regarding the empirical case can be explained by the fact that all agricultural freight trips include at least one truck component in the full journey from farm to final destination, with trucks being the dominant choice of mode within 750-mile distances.<sup>41</sup> So, in the empirical case, individual cereal grain commodities start from Midwest—the production region—and are most heavily distributed to nearby states via highways.<sup>42</sup> But for around 2000 miles transits, railways (e.g., East Coast–West Coast) and waterways (e.g., Mississippi riverbed) are more preferred mode choices due to their economies of scale property within the associated fixed costs of transit.<sup>43</sup> Further, the total delivery time and service reliability standards imposed on freight transit firms often translate into relying mainly on highways to ensure fast delivery, high-quality service, and consistent performance.<sup>44</sup> This can also explain the resemblance between the empirical case and the most adaptable scenario in terms of both spatial and individual commodity mass trends.

Here, our findings under optimization scenarios are descriptive and confirmatory, as they are driven mainly by the empirical characteristics of individual transportation infrastructures and U.S. cereal grain supply chains. For instance, illustrating that the majority of cereal grain mass transit around the Midwest and adaptability optimization scenario to not allocate mass to waterways aligns with anticipated real-world trends. Further, FAF-scale spatial trends in the proposed cost-efficient and sustainable solutions align with previous literature<sup>45,46</sup> that identifies the major waterway transit ports for domestic agri-food freight.<sup>47</sup> Thus, these observations give us confidence in our approach and hope that the potential improvements, when it comes to the sustainability of cereal grain transit—achieving less carbon dioxide emissions during the nationwide distribution—can be practically implementable. Yet, we highlight that efforts to address sustainability should consider the trade-off with resilience.

**Policy Implications.** It will be increasingly important to balance cost, emissions, and adaptability in cereal grain transit going forward. During the COVID-19 pandemic, food price inflation soared<sup>48</sup> and reduced access to affordable food supplies for domestic food security.<sup>49</sup> This reiterated the importance of prioritizing cost in staple grain supply chains, as these commodities are the main source of daily nutrition for low-income and food-insecure groups.<sup>50</sup>

However, multicereal transportation planning also needs to consider how to be adaptable during shocks. Distributing such essential goods in the most resilient way is an important criterion, particularly in times of disruptions. Recently, freight transit within the U.S. has been halted due to weather extremes (e.g., Hurricane Katrina caused floodings<sup>51</sup> and Mississippi river water height decreases during droughts),<sup>52</sup> infrastructure deterioration (e.g., Baltimore bridge collapse),<sup>53</sup> and labor strikes (e.g., 2022 railroad labor strike),<sup>54</sup> which collectively highlight the importance of maintaining agri-food supply chains during shocks as a key contributing factor to national food security<sup>55</sup> and economic stability.<sup>56</sup>

Our findings illustrate that the current state of region-to-region cereal grain transit relies heavily on highways. Yet, there is also cereal grain transit along the East–West railways and waterways along the Mississippi river, where the reasons for such mode choices might be shaped by the logistics cost, nature of goods, and spatial characteristics of infrastructure.<sup>57</sup> Moving forward, freight transit planning could benefit from more cost-efficient strategies, as the current situation seems to be relatively adaptable. Such strategies to rely more on railways, particularly as they can connect the entire CONUS to each other, could also address carbon emission concerns without sacrificing adaptability to a degree. Given the scope of our findings, which excludes intracity and last-mile deliveries, policies to reduce truck traffic along the interstate and state highways, especially for the transit of nonperishable goods, could be further evaluated through a comprehensive cost vs benefit analysis.

**Advantages, Limitations, and Future Work.** This study assesses the actual transit patterns of the multimodal and multicereal grain supply chain in the United States. It further proposes strategic cereal grain mass allocation onto real-world highways, railways, and waterways within the United States to optimize transit cost, emission, and adaptability goals. Our findings could inform national programs, as we pinpoint which mode-specific transportation paths are currently being most heavily utilized. We also highlight which paths can be utilized

to promote more cost-efficient, sustainable, and resilient systems. Thus, ongoing efforts could ensure that the economic efficiency and resilience of the U.S. agri-food transit systems are not undermined<sup>58</sup> while increased attention is placed on improving their sustainability.<sup>59</sup>

One limitation of our study is that it is heavily data-driven, inheriting the underlying limitations of FAF data. For instance, we are not able to capture intracity or last-mile deliveries of commodities with a granular time step, as FAF data records annual total nationwide freight movement. The heavy reliance on highways for cereal grain transit that is captured here is only for the nationwide distribution between FAF zones as an aggregated annual trend. Thus, our study is not able to capture granular logistical transportation issues such as vehicle scheduling, lane capacity, or path congestion. Further, the annual time step limits our ability to capture subannual storage dynamics<sup>60</sup> functioning of locks and dams along the Mississippi River<sup>36</sup> and capacity fluctuations in rail tracks,<sup>61</sup> which are important in grain systems. However, such issues impact freight mode choice as they collectively determine spatial infrastructure characteristics and firm-level logistics preferences.<sup>57</sup> Therefore, our approach could be improved by further including factors such as time sensitivity, volume variability, and finer-granular infrastructure availability that can influence practical freight transit decisions.

Future research could build upon our study and conduct shock simulations on the transportation modes to test how potential investments and new rerouting strategies would impact the efficiency, sustainability, and resilience of cereal grain transit. In addition, our analysis (e.g., cost-emission-adaptability metrics as well as multiobjective optimization model) could be extended to the transit of other food commodities, specific U.S. regions, or other countries based on data availability. Extending our study to countries in the Global South<sup>62</sup> would be particularly critical, as they are facing food security issues and are in need of better-informed infrastructure investments. Our data-driven optimization model could be applied to other countries with suitable data to evaluate opportunities to balance efficiency, resilience, and sustainability in their supply chains.

## ■ ASSOCIATED CONTENT

### Data Availability Statement

All data sources are listed in the methods section of the paper and are freely available online. Freight Analysis Framework (FAF) scale empirical cereal grain transit data is collected from <https://faf.ornl.gov/faf5/Default.aspx>. The spatially located shapefiles of U.S. highways, railways, and waterways are collected from <https://rosap.nrl.bts.gov/view/dot/7547>.

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.5c00909>.

Infrastructure shapefile cleaning; QGIS-RStudio cross-walk to generate spatial networks; data assumptions; network statistics; and adaptability metric; impact of mode-specific foundational characteristics on cost-emission-adaptability metrics; comparison of our novel adaptability metric vs Shannon diversity index, Herfindahl-Hirschman index, and network path redundancy measure (PDF)

## Accession Codes

Code for calculating the cost, emissions, and adaptability metrics for real-world transportation infrastructure-based cereal grain transit between FAF zones is developed in RStudio 4.0.2. The multicommodity, multimodal, and multi-objective optimization model is developed in Jupyter 7.0.8. All code will be made available upon reasonable request from the corresponding author.

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### Notes

The authors declare no competing financial interest.

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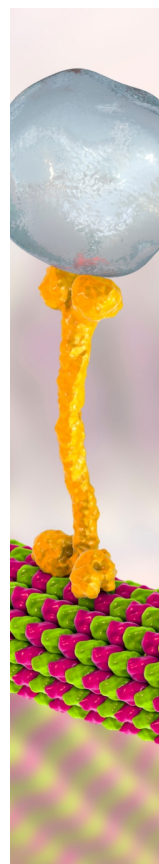
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