REPORT

Modeling the dynamic impacts of maritime network blockage on global supply chains

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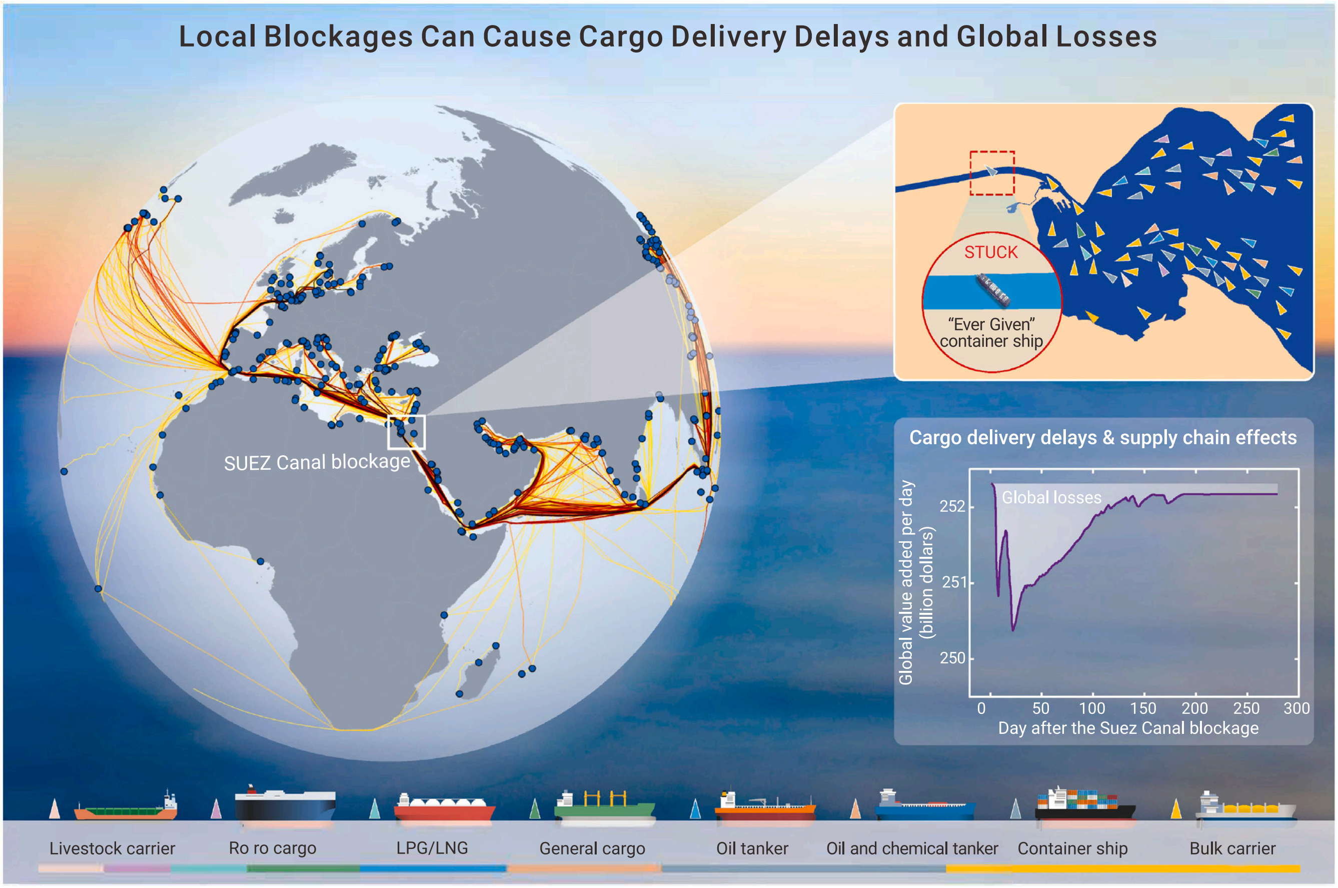
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- We estimate the second-to-hourly updated trajectories of 432 delayed vessels and their carried cargo values.
- An adaptive multi-agent model is developed to simulate cargo blockage and its daily impact on supply chains.
- Modeling shows that India accounts for 75% of global losses from the Suez Canal blockage impacts.
- Global losses and blockage duration have a nonlinear relationship, with losses escalating rapidly after 5 days.

Modeling the dynamic impacts of maritime network blockage on global supply chains

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Recent phenomena such as pandemics, geopolitical tensions, and climate change-induced extreme weather events have caused transportation network interruptions, revealing vulnerabilities in the global supply chain. A salient example is the March 2021 Suez Canal blockage, which delayed 432 vessels carrying cargo valued at $92.7 billion, triggering widespread supply chain disruptions. Our ability to model the spatiotemporal ramifications of such incidents remains limited. To fill this gap, we develop an agent-based complex network model integrated with frequently updated maritime data. The Suez Canal blockage is taken as a case study. The results indicate that the effects of such blockages go beyond the directly affected countries and sectors. The Suez Canal blockage led to global losses of about $136.9 ($127.5–$147.3) billion, with India suffering 75% of these losses. Global losses show a nonlinear relationship with the duration of blockage and exhibit intricate trends post blockage. Our proposed model can be applied to diverse blockage scenarios, potentially acting as an early-alert system for the ensuing supply chain impacts. Furthermore, high-resolution daily data post blockage offer valuable insights that can help nations and industries enhance their resilience against similar future events.

INTRODUCTION

Global supply chains have greatly expanded in recent decades, becoming essential for the economic prosperity and resource security of many countries.[1] Maritime transportation is a cornerstone of this complex network, given its efficient transportation infrastructure and cost-effective operations; it accounts for 75% of global trade volume and 50% of trade value.[2] Thus, blockages of maritime trade routes pose substantial threats to the security of global supply chains.[3] The vital nodes in the maritime network, such as ports, canals, and straits, face high blockage risks[4,5] (Table S1) owing to unexpected events such as pandemics and geopolitical tensions.[6] Moreover, with increases in climate change-related extreme weather events,[7] such as storms[8] and severe droughts,[9] these critical nodes in maritime networks face increased risks of congestion and disruption.[10,11]

These increased risks of transportation disruption against the background of complex global linkages warrant investigating the effects of recent disruptions on supply chain networks.[12] Studies have aimed to quantify the ramifications of road,[13] inland waterway,[14] and port disruptions,[15] focusing on areas such as operational transportation costs,[16] shipper and carrier costs,[17] reputation loss, and port business loss.[18] Regarding supply chain losses, studies have used indicators such as increased transportation time,[12] associated costs,[19–21] and the extent of transportation infrastructure damage[22] to quantify the degree of disruption. However, the impacts of disruptions often go beyond these metrics. Interruption could lead to reduced production when delays of raw materials exceed inventory holding periods, precipitating a ripple effect throughout the supply chain and causing further cascading losses.[23] Thus, the above indicators along with the value of delayed cargo have been incorporated into computable general equilibrium (CGE) models,[12,19,21,22,24] input-output models (for port disruption),[25] and Petri net models[26] to evaluate the cascading effects of disruptions on the overall supply chain. However, such research has focused solely on the total value of delayed goods in specific regions, often overlooking critical details pertaining to the characteristics of these goods. Moreover, existing models are limited in terms of effectively simulating the adaptive behavior of supply chain networks when faced with supply shortages owing to interruptions. Since they usually operate on an annual timescale, these models have difficulty accounting for short-term disruptions or blockages.

A recent study revealed the effect of climatic-related port downtime on global trade and economic activity.[27] However, that study did not incorporate adaptive behavior. Another study developed an agent-based supply chain model to simulate the impact of road disruptions in Tanzania.[28] That model, however, inadequately captured mechanisms such as the substitution effects of homogeneous products between different regions[29] and weekly simulation. A numerical agent-based shock model was developed to study the regional and global economic effects of short-term disruptions in the Western Pacific trade route caused by typhoons.[30] The model was based on profit maximization as a behavioral criterion, but this did not align with real-world micro-level behavioral norms based on habit (see Text S1). Thus, there remains a gap in research on the evaluation of total losses resulting from short-term blockages. In particular, it is important to incorporate data on daily cargo flows and delays arising from unexpected events.

This study, therefore, proposes a daily resolution loss-assessment model based on adaptive agents to simulate the cascading impacts of shipping blockages in supply chain networks. The model operates on a daily time step based on the postdisaster behaviors of supply chain network agents, such as mobilizing excess capacity and inventory, reselecting trade partnerships, adjusting production technologies, and undertaking reconstruction after a disaster. Our model allows a large number of production, consumption, and transportation agents to interact in a complex network, simulating the daily evolution of outputs under a given shock and calculating the losses through comparisons with initial steady-state values. We use the model to assess the daily global losses resulting from the 2021 blockage of the Suez Canal, a vital maritime route situated on the western side of the Sinai Peninsula in Egypt (Figure 1B). Previous studies of this incident focused on its causes and the lessons learned,[4,31] descriptive analyses of its effects on global supply chains and its legal implications,[32] and its influence on the global shipping network[33] and crude oil prices.[34]

Incidents such as the Suez Canal blockage are expected to greatly affect global supply chains, potentially causing massive but unknown losses to many countries and sectors. Thus, we couple the shipping network with the supply chain network to simulate and evaluate the impacts of the Suez Canal blockage on the global trade system. First, we collect empirical vessel data from the Automatic Identification System (AIS) dataset, which provides information on the affected vessels during the study period. Second, based on that information, we estimate the volume and monetary value of blocked cargo in the global supply chain network. Then, using our agent-based complex network model, we simulate the production decline caused by cargo delays and the cascading losses transmitted through the supply chain. We then analyze the heterogeneous impacts of blockage on various countries and sectors. Furthermore, we perform scenario analyses to measure the impacts of varying durations of blockage on global supply chains. Sensitivity analysis is conducted to evaluate the proportion of losses and the losses caused by a delay of one dollar for different types of cargo.

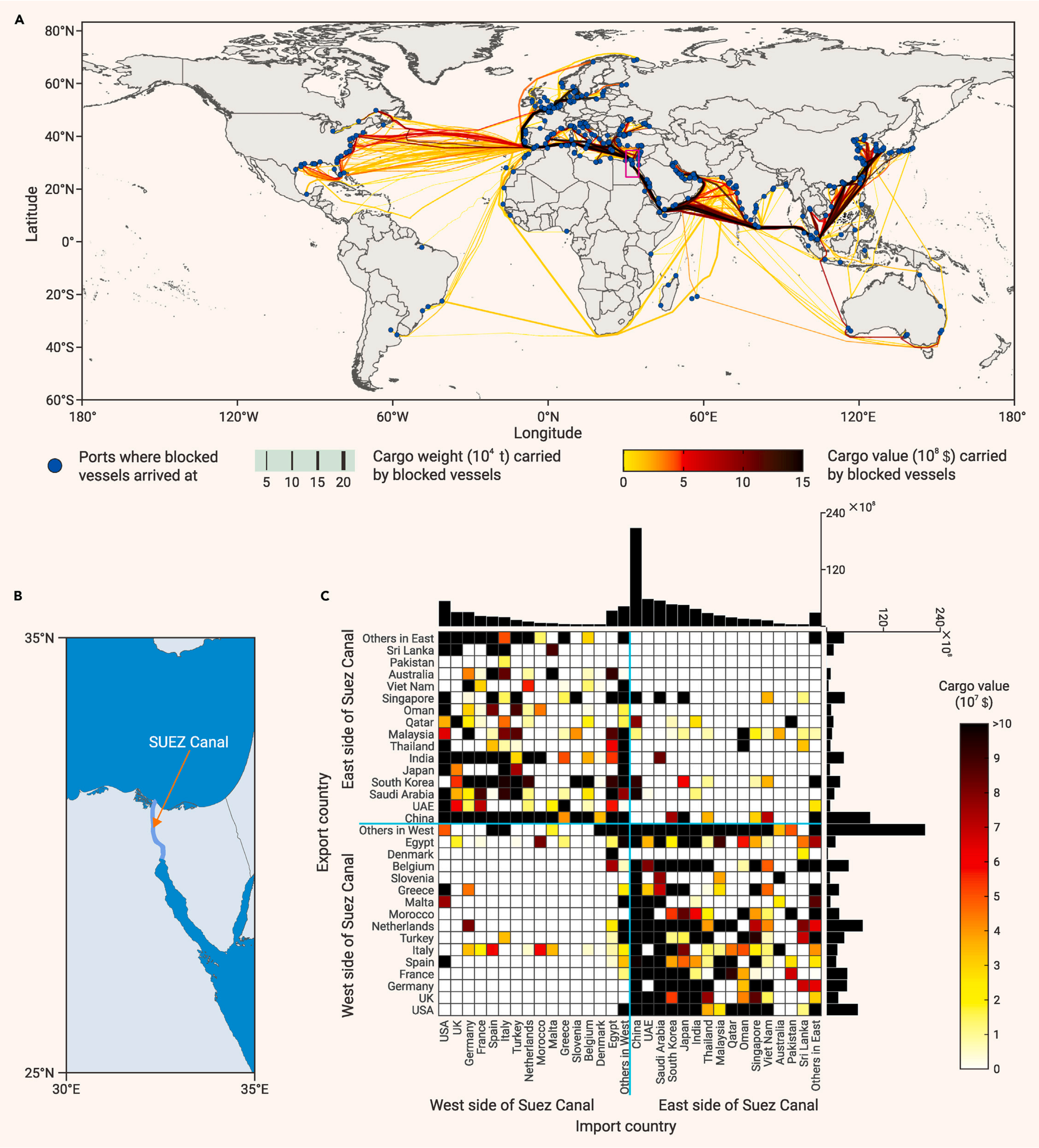

Figure 1. Trajectory and value of vessels and cargo affected by the Suez Canal blockage (A) Trajectory of the blocked vessels. The size of the trajectory represents the weight of cargo transported on these vessels; the color represents the monetary value of cargo on these vessels. (B) Location and schematic diagram of the Suez Canal. (C) International matrix of blocked cargo value. Countries are divided into two groups according to whether they are located on the west or east side of the Suez Canal. In each group, countries are arranged in descending order of cargo imports; those without notable cargo value are merged into "Others in West" and "Others in East."

RESULTS

Suez Canal blockage

Beginning on March 23, 2021, the Suez Canal faced a 175-h blockage (~7.3 days) caused by the grounding of the container vessel *Ever Given* (see Text S2). We estimate the weight and value of cargo transported by blocked vessels based on vessel movement data and the BACI database[35] (see materials and methods for details). Figure 1A shows the origin-destination routes of 432 vessels that were affected by the Suez Canal blockage. The weight and monetary value of cargo transported by these vessels between countries are indicated by the size and color of the lines on the map. Among the affected vessels, loaded

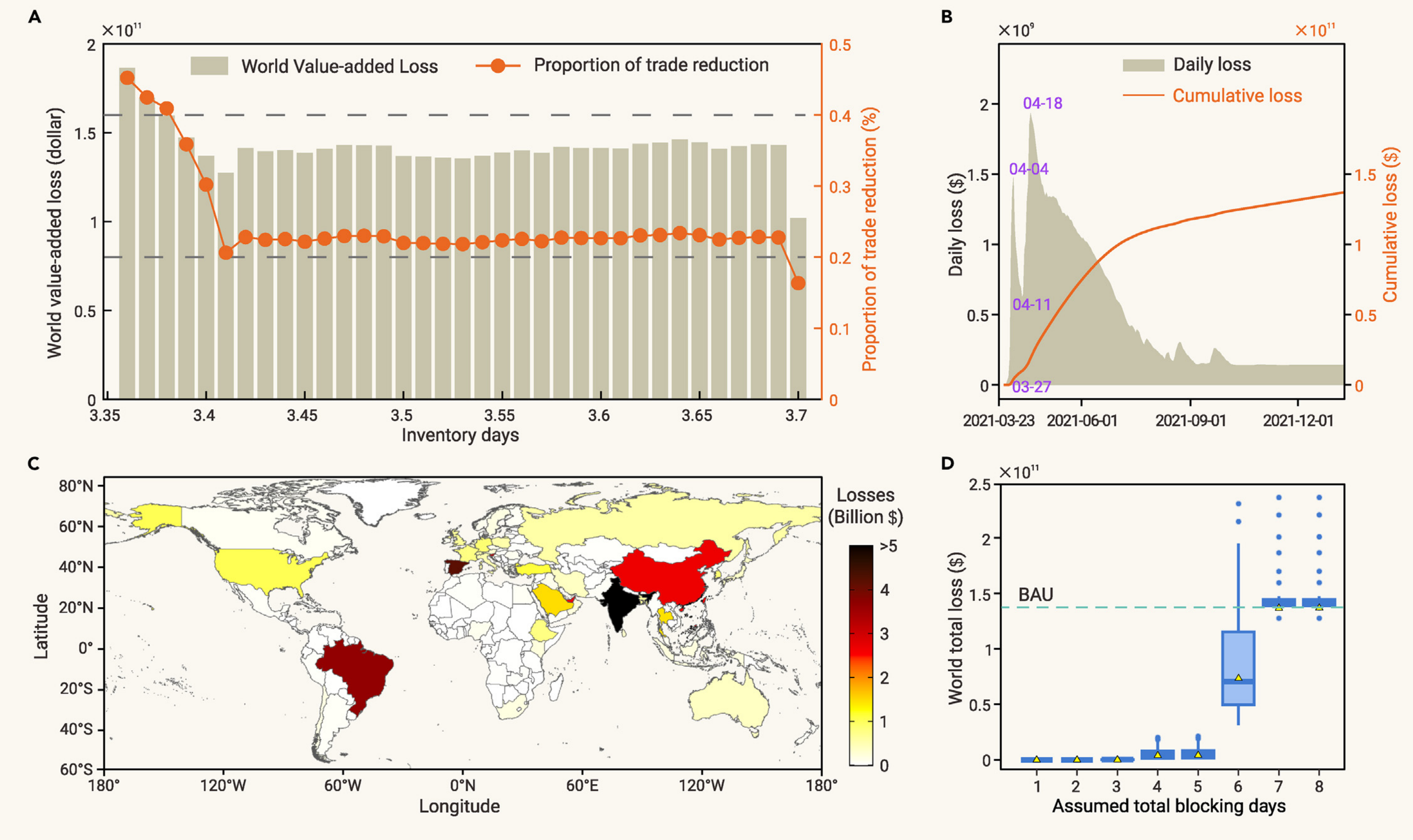

Figure 2. Total value-added losses from the Suez Canal blockage at the global and country levels (A) Value-added loss and trade decrease proportion under different inventory days. The proportion of the decrease in the value of global trade is obtained by the ratio of trade loss caused by the Suez Canal blockage to trade value in 2020. (B) Simulated global daily and cumulative loss owing to the Suez Canal blockage. (C) Value-added loss from Suez Canal blockage in each county. Color shades represent the loss of value added by countries. (D) Global total loss under different counterfactual scenarios, assuming the Suez Canal was blocked for only 1 day, 2 days, and so on, up to 8 days. For each scenario, we calculate the global value-added loss under the reasonable inventory size (interval 0.01; a total of 31 cases). The dashed line in the figure represents the total global loss under the selected inventory size under the actual duration of the Suez Canal blockage.

vessels (372 in total) and empty vessels (60 in total) are mapped separately in Figure S1. The results show that 25.8 million tons of cargo, with a total value of $92.7 billion, were blocked; these figures differ by only 2% and 10%, respectively, from data published by canal officials and the media (Text S3).

The affected trajectories were mainly between the United States, Europe, the Middle East, India, and East Asia, pertaining to the trade volume, geographical location, and distribution of trade objects in each country or region. Figure S1 further details the trajectories of blocked vessels heading to these regions. Among all of the vessels, two crude oil vessels (one traveling from Norway to India and another from Saudi Arabia to Egypt) carried the heaviest cargo (nearly 0.3 million tons each). Blocked vessels with high cargo values mainly operated between China and Europe. Notably, three European container vessels each carried cargo values of over $1.5 billion.

By aggregating the value of cargo transported by blocked vessels at the country level, we obtain an international matrix of blocked cargo values (Figure 1C). Among the nearly 700 blocked cargo flows at the country level, the top 10 high-value flows account for 19.8% of the total blocked cargo value. Noteworthy high-value flows in the matrix include cargo flows from the Netherlands, Germany, and Belgium to China (9.3%); from China to Germany (1.8%); from the United States and France to Saudi Arabia (3.2%); and from China to the United States (1.3%). In terms of the accumulated blocked cargo value by country, China ranks first for both imports (22.6%) and exports (9.1%), reflecting the huge trade volume between China and Europe. Moreover, Figure S2 summarizes the compositions of blocked import and export cargo value by country. The results show that 31.9% of cargo value comes from electrical and machinery products (mainly exported from Europe to East Asia and the Middle East); 19.1% comes from petroleum products (mainly exported from the Middle East to Europe). The blocked cargo value matrix in Figure 1C is divided into four quadrants. Among them, the cargoes in the second and fourth quadrants, accounting for 89.5% of the value of blocked cargo, were transported by the blocked vessels crossing the Suez Canal from east to west or west to east, reaching their destination ports after the blockage was resolved. Meanwhile, some vessels pass through the Suez Canal without cargo, subsequently facing delayed loading for their next shipment. Thus, a small portion of cargo carried by these vessels is situated in the first quadrant (east to east) or third quadrant (west to west), accounting for 10.5% of the value of blocked cargo.

Impacts on global supply chains

Blockages can lead to delays in cargo delivery, resulting in shortages of raw materials, which can cause production declines and supply chain losses. Considering this, we develop an agent-based complex network model to simulate the impacts of the Suez Canal blockage on global supply chains (see materials and methods for details). Since the model yields different losses for varying inventory levels, we use external macroeconomic data provided by Allianz as constraints. According to these data, every week of the Suez Canal closure should have resulted in a reduction in global annual trade growth of 0.2%–0.4%.[36] The inventory days in our agent-based complex network model are 3.39–3.69 days, and the corresponding global value-added loss ranges from $127.5 to $147.3 billion (Figure 2A, Text S4). In our main analyses, we use 3.5 inventory days to evaluate the effect of the Suez Canal blockage, with losses at this inventory level being close to average losses.

Figure S3 and Video S1 show the evolution of losses in the supply chain network, offering insights into blockage-related losses. We observe two phases in the losses: initially, cargo delays caused by the blockage contribute to losses. In the second stage, the cascading effect in the supply chain network becomes the main cause. Figure 2B presents the daily evolution of global total value-added losses resulting from the Suez Canal blockage. The gray area indicates the daily dynamics of value-added losses, which first appear on March 27 (4 days after the blockage began). This is because the cargoes transported by vessels originally scheduled to arrive in Egypt and Saudi Arabia—which are located near the

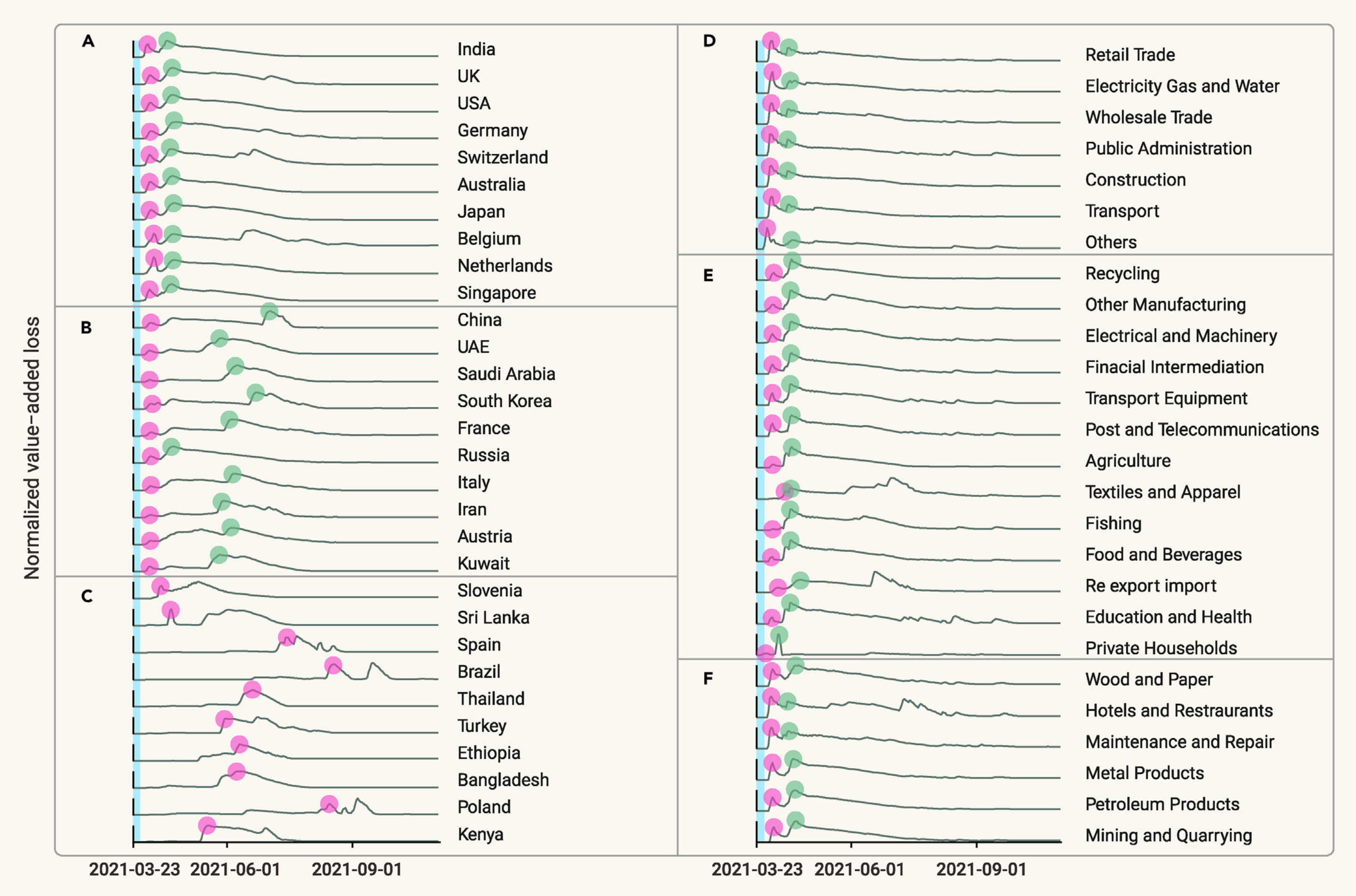

Figure 3. Normalized daily value-added losses of countries and sectors Normalized daily value-added loss curves of countries (A–C) and sectors (D–F). We select the top 30 countries based on the percentage of annual value-added loss and all of the sectors in Eora.[38,39] Based on the number of peaks and the relationship between the two peak heights in the loss curves (the first peak is marked with a pink point and the second with a green point), we divide the selected countries and sectors into three groups. The two peaks are about the same height (A and F); the first wave crest is lower (B and E) and higher (D) than the second; there is only one obvious crest (C).

Suez Canal—on March 23 were delayed for 4 days, exceeding the inventory size for these regions. This delay then led to raw material shortages, production declines, and losses. As the blockage continued, more cargo was delayed, with losses peaking on April 4. Subsequently, as the blocked vessels started to arrive at their destinations (India and Western Europe), the delayed cargoes were delivered, and production recovered. Losses began to decline reaching a low point on April 11, with most blocked vessels finally arriving at their destinations (including the United States and East Asia). Therefore, we can roughly attribute the first peak to direct losses, which were value-added losses resulting from production interruption caused by the delay of cargo exceeding inventory. Losses began to rise once more as direct losses spread throughout the supply chain, culminating in indirect losses, as indicated by the second peak on April 18, as shown in Figure 2B. We can reasonably attribute the second peak in losses to indirect loss.

Figure 2C shows the value-added losses incurred by countries as a result of the Suez Canal blockage. Out of the total economic loss of $136.9 billion, India faced the most significant loss, amounting to $102 billion (equivalent to 3.8% of its GDP), followed by Spain, Brazil, China, and the UAE, whose losses range from $2 billion to $4 billion. We observe that countries with more losses are situated in coastal areas, while those in Central Asia and Africa incurred considerably lower losses, nearly approaching negligible levels. The Suez Canal blockage had a more significant impact on India than on other countries; this can be attributed to two main factors. First, India's manufacturing industry is heavily reliant on imported raw materials from Europe and the United States.[37] Second, the blockade raised transportation costs for exported Indian goods. Factors such as a decrease in factory profits and an inability to transport goods to Europe and the United States in a timely manner led to the suspension or cancellation of some orders (see Text S5 for specific details).

The Suez Canal remained blocked for about 7.3 days. Based on daily blocked cargo data (Figure S4) and our daily-scale simulation model, we calculate total global production losses under eight counterfactual scenarios (e.g., the Suez Canal was assumed to block for a total of 1 day, 2 days, … 8 days; see scenario analysis in materials and methods). As shown in Figure 2D, when blockage persists for fewer than 4 days, thanks to inventories, there is almost no production decline or loss. However, when blockage persists for 4 or 5 days, some production agents begin depleting their inventories, leading to raw material shortages, reduced production, and average supply chain losses of $5.8 billion. If blockage lasts 6 days, supply constraints extensively permeate the supply chain, resulting in a substantial loss of about $89.9 billion. Losses incurred under 7 days of blockage amount to $149.9 billion, which is nearly identical to that for an 8-day blockage. The results of the counterfactual analysis indicate that, in the event of a blockage of the Suez Canal, aiming to dredge the canal and restore navigation within 5 days can significantly reduce the impact on global supply chains.

Country- and sector-level loss propagation

Figure 3 shows the daily evolution of losses across countries and sectors. We can see that the loss curves have different numbers of peaks. Similar to Figure 2B, the initial peak is mainly attributed to direct losses resulting from production interruptions caused by cargo delays surpassing available inventory; the second peak mainly represents indirect losses stemming from the propagation of direct losses throughout the supply chain.

By examining the number of peaks and the relationship between their heights, we analyze the types and causes of losses in each country and sector. Notably, the two peaks in the curves of Figures 3A and 3F have similar heights, indicating that these countries and sectors faced significant direct and indirect effects. By contrast, the first peak in the curve in Figure 3D is much higher than the second

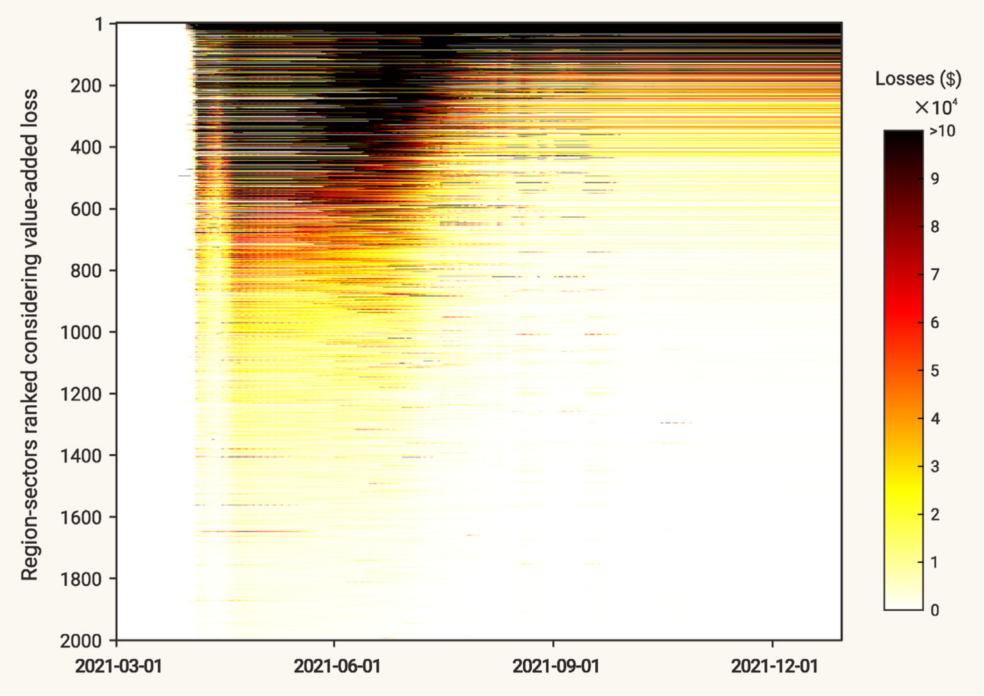

Figure 4. Daily value-added losses of region-sectors Horizontal axis is the selected date (March 1, 2021 to December 31, 2021). The vertical axis is in descending order of total region-sector loss, and the number represents the order. The color represents the daily loss of each region-sector.

peak, indicating that these sectors were mainly affected directly and to a lesser extent indirectly. While the losses in Figures 3B and 3E appear immediately after the end of the blockage, the height of the first wave is comparatively low, whereas the losses in Figure 3C occur sometime after the end of the blockage. This suggests that the countries in Figures 3B and 3C and sectors in Figure 3E suffered fewer direct impacts, with most of the loss transmitted through supply chain effects from other countries and sectors. Based on the type and extent of impact on countries and sectors resulting from the Suez Canal blockage, targeted measures for loss reduction can be implemented (Text S6).

Figure S5 provides an overview of value-added losses by sector groups. While the proportion of losses is relatively small, the financial intermediation sector shows the largest value-added loss owing to its substantial GDP. Conversely, sectors such as agriculture, recycling, textiles, and apparel show losses that account for a significant proportion of their annual GDP, mainly attributable to supply chain effects. We conduct a sensitivity analysis of the losses caused by delayed cargo, considering both the proportion of losses attributed to different types of cargo and the losses caused by a delay of one dollar for different types of cargo. Petroleum, chemical, and non-metallic mineral products, along with electrical and machinery products, contribute substantially to overall losses, each accounting for over 16%. As for losses caused by a one-dollar cargo delay, fishery, metal products, and mining and quarrying products incur higher losses (Figure S6). Figure S7 depicts the losses caused by delays in energy-related cargo.

We compute the 365-day loss of all of the region-sectors and select the top 2,000 region-sectors with the highest value-added loss to illustrate the global impact of the Suez Canal blockage in Figure 4. Among the first 200 region-sectors, daily value-added losses exceed $0.1 million from the onset of the Suez Canal blockage until the end of the simulation, signifying a sustained supply chain impact lasting throughout the year. These 200 region-sectors (Table S2) include all of the sectors in India and the majority of sectors in Spain, Brazil, and Slovenia. Additionally, approximately half of the sectors in UAE, Saudi Arabia, and China, as well as about one-third of the sectors in Thailand, the United States, and Germany, fall into this category. Some countries have only one or two sectors in the first 200 region-sectors, and most are in the mining and quarrying sector, followed by the financial sector, metal products sector, and petroleum products sector. As for the remaining region-sectors, losses last about 3 months before gradually reducing to zero. This trend could be related to the small amount of cargo affected by the blockage in these specific region-sectors.

Scarcity

We compute the daily evolution of scarcity indices for sectors across different countries, as shown in Video S2. In the 365-day simulation, May 18, 2021, shows the highest level of scarcity. Thus, Figure 5 depicts the scarcity index of the selected country-sectors on this day. The results show that the product scarcity indices of all of the sectors in Slovenia (except private households) exceed 0.1, indicating that more than 10% of demand is not met, resulting in a production decrease and value-added loss. The average value of the product scarcity index of 26 sectors in Slovenia on May 18, 2021, is 0.228, which is roughly equal to 29.6% of GDP loss on that day. The product scarcity index of the hotels and restaurants sector in the UAE and the recycling sector in Turkey exceeds 0.1, making them the main sectors contributing to value-added losses. Therefore, to cope with the supply chain impact caused by the blockage, these seriously affected region-sectors should appropriately increase their inventories and overcapacity proportion to reduce losses.

DISCUSSION

Understanding the global impacts of maritime network blockages

This study presents a method for simulating the dynamic effects of maritime network blockages on intercountry supply chains. Employing a multi-agent complex network model in conjunction with empirical vessel tracking data, we uncover the intricate interplay of factors such as blockage, scarcity of goods, direct and indirect impacts on supply chains, and the evolution of supply chain networks. Addressing such complexity requires a comprehensive understanding of the spatial and temporal heterogeneity inherent in these factors, which is pivotal for effective blockage-management strategies.

The results show that total losses worldwide are approximately $136.9 billion, ranging from $127.5 to $147.3 billion. Notably, losses in India account for about 74.5% of the total loss, which is far greater than the proportion of blocked cargo value (4.1%) in the country. This indicates that blocked cargo value is not the sole determinant of output losses caused by the Suez Canal blockage. Our finding that India was seriously affected by the Suez Canal blockage aligns with a previous report.[40] Different from India, China had the highest blocked cargo value (22.6%) but faced lower output loss (1.9%) due to its relatively complete industrial system. Also, highly import-dependent cargoes in China (e.g., oil and mineral resources) were not affected by the blockage. In addition, output losses in Europe accounted for about 10% of total losses. This differs from the view of some supply chain experts who thought the European market would be the most affected.[41]

Enhanced modeling approach

Our research represents a significant advancement over prior studies in several key aspects. First, in terms of scope, we focus on simulating short-term transportation blockages that frequently occur in reality, as opposed to the long-term transportation disruptions investigated in previous studies.[24,26,27,42] In previous research, “disruption” has referred to the complete impairment of an entire transportation route, rendering cargo transport between two regions impossible. By contrast, in our context, “blockage” means that cargo can be delivered and transported in a steady stream between two regions, but a node is temporarily blocked, causing cargo accumulation in that place for a short time.

Second, our research significantly enhances data resolution. Unlike earlier studies that mainly assessed losses at annual,[42] monthly,[43] or weekly[27] intervals, we use second-to-hourly updated AIS data to analyze blocked cargo and simulate losses at a daily resolution. This dataset offers comprehensive information

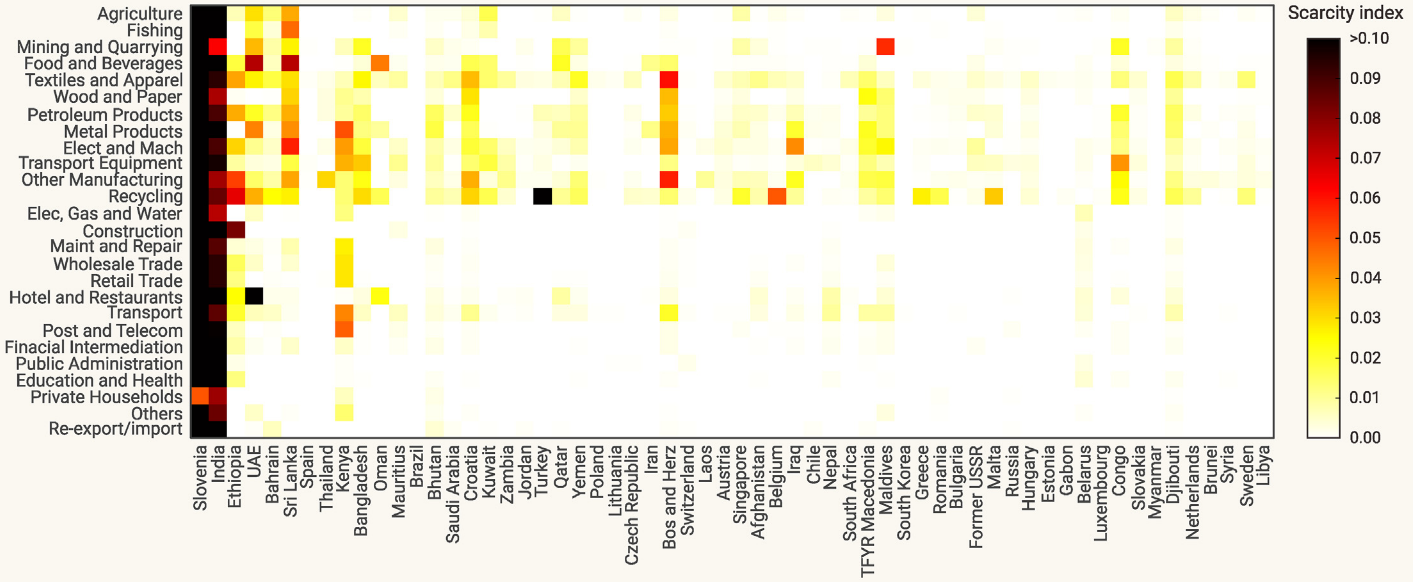

Figure 5. Scarcity index of each product in selected regions The horizontal axis is the top 60 countries in terms of value-added loss proportion. Vertical axis is the sectors of Eora, and each sector corresponds to a product. Scarcity indices are defined as (product demanded − product supplied)/(product demanded). If this index is >0, supply cannot meet demand.

about basic ship characteristics, route information, shipping information with timestamps, and sectors affected by delayed cargoes. This rich dataset has higher spatial and temporal resolution, facilitating the implementation of a daily modeling approach. Consequently, our results are more finely detailed in both spatial and temporal aspects, enhancing the precision of our analysis.

Third, we introduce innovative approaches to supply chain impact simulation. Traditional models such as the input-output model assume that the ratio of production factors and prices remains fixed and linear, thereby failing to capture the adaptive behaviors of economic systems under blockage shocks.[44] The CGE model assumes market equilibrium and adjusts prices to adapt to external shocks, making it difficult to accurately capture sudden short-term shocks owing to blockage.[45] By contrast, our agent-based complex network model integrates several habit-based micro-level adaptive behaviors in a unified framework, aiming to describe model mechanisms using the simplest mathematical formulas and language possible. For blockage simulation, we introduce a novel approach. While previous studies simulated interruption impacts by simply eliminating the disrupted route from cargo transportation networks,[27] our method provides a more realistic simulation by including the processes of loading, transporting, blockage, and unloading between agents in the supply chain network, thus achieving a more realistic simulation of vessel blockage.

Policy implications

Our simulation of the Suez Canal blockage event has implications for governments and industry stakeholders. It emphasizes that the repercussions of such blockages extend far beyond the countries directly affected by import delays. The ripple effect throughout the global supply chain results in reduced orders for raw materials from upstream suppliers, leading to supply shortages for downstream customers. This highlights the vulnerability and interconnectedness of international supply chains, emphasizing the urgent need for comprehensive measures to enhance supply chain resilience.

Additionally, blockage duration is a critical factor influencing global value-added losses. When a blockage persists for a period shorter than the typical inventory size (e.g., 4 days), losses remain relatively minor thanks to the buffer provided by existing inventory levels. However, when blockage duration extends beyond this inventory threshold, losses escalate significantly. Therefore, policymakers should prioritize swift resolutions, aiming to resume canal passage before inventory depletion occurs. This strategic approach could be highly effective for minimizing global losses and ensuring the smooth flow of goods through the canal.

Furthermore, our research has the potential to serve as an early-warning system for the global economic community. By predicting product shortages at specific times and in specific regions, policymakers can proactively address potential supply chain impacts. Leveraging the scarcity index, governments and industry players can implement targeted policies and strategies to bolster inventories of critical products before shortages occur. This proactive approach not only reduces the impact of maritime network blockages but also helps manage long-term inventory costs, ultimately contributing to a more resilient global supply chain ecosystem.

Limitations and future research

Faced with constraints related to trade relationships in the multi-regional input output (MRIO) framework and uncertainty estimating the value of delayed cargo, we set a constant inventory size for all of the region-sectors. Our proposed quantitative modeling framework can be extended to assess the significance of key maritime network nodes and the potential cost-effectiveness of various congestion-mitigation measures. Future investigations can aim to further enhance preparedness, response, and resilience in the face of global-scale supply chain interruptions (see Text S7 for details).

MATERIALS AND METHODS

See the supplemental information for details.

DATA AND CODE AVAILABILITY

The AIS data are restricted to the third party and used under license for this study. The Eora26 database is available at Eora26: https://worldmrio.com/eora26. Data for intercountry trade flow come from the BACI database, available at BACI database: http://www.cepii.fr/CEPII/fr/bdd_modele/bdd_modele_item.asp?id=37. Shipping distances between 189 countries come from the CERDI SeaDistance database (CERDI database: https://zenodo.org/record/46822#.Yn9dVYxByUk). GDP growth rate and inflation rate come from Trading Economics (https://zh.tradingeconomics.com/united-states/inflation-cpi), OECE (https://www.oecd.org/economic-outlook/march-2021/), and the World Bank (https://data.worldbank.org.cn/indicator/NY.GDP.MKTP.KD?).

The codes used in this study are available from the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

S.Q., Y.S., and Q.Z. conceived the study and performed the analysis. Y.S., J.V., and H.L. contributed to the data collection and processing. Y.S. and S.Q. analyzed the data and implemented the model. Y.S., Q.Z., and J.V. contributed to preparing the figures. S.Q., Y.S., Q.Z., J.V., L.-T. Z., M.X., and Y.-M.W. contributed to the writing and reviewing of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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