FIRM-LEVEL PROPAGATION OF THE EFFECT OF DISRUPTION OF INTERNATIONAL TRADE THROUGH DOMESTIC SUPPLY CHAINS

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ABSTRACT

Risks of disruption to global supply chains are rising and threatening the sustainability of global supply chains. This study simulates how the disruption of imports from various regions affect the total production of Japanese firms. We particularly incorporate the propagation of the economic effect through domestic supply chains, using data on more than one million firms and four million supply chain ties. We find that the negative effect of disruption of intermediate imports grows exponentially as its duration and level increase because of downstream propagation. In addition, the propagation of the economic effect is substantially affected by the network topology of importers, such as the number of importers (affected nodes) and their upstreamness in supply chains, but not necessarily by their centrality. Furthermore, the negative effect of import disruption can be mitigated by reorganisation of domestic supply chains, even when the reorganisation is conducted among only network neighbours.

Keywords: global supply chains, trade disruption, network analysis.

1 INTRODUCTION

Sustainability and resilience of global supply chains, i.e., the network of trade in material and parts for production across countries and industries, are currently threatened. In recent years, global supply chains have frequently been disrupted by coronavirus disease 2019 (COVID-19) (Friedt and Zhang 2020, Guan et al. 2020, Meier and Pinto 2020), natural disasters, such as the Great East Japan earthquake (Barrot and Sauvagnat 2016, Carvalho et al. 2021), military conflicts, such as the Russo-Ukrainian War (Kilpatrick 2022), and policies to "decouple" between the United States and its allies and China (Todo 2022). The risk of the disruption of global supply chains has been rising because products and services have developed. In addition, the disruption risk has been intensified because of increasing possibilities that countries "weaponize" supply chains by restricting trade with particular partners for national security reasons, as global geopolitical risks soar (Farrell and Newman 2022, Fuller 2022).

Global supply chains contribute to the economic efficiency by allocating production processes across countries depending on their advantages and thus benefit both developed economies that are hubs of supply chains and developing economies that recently participate in supply chains (Baldwin 2016). Therefore, the possible disruption of global supply chains in a large scale would jeopardise the sustainability of the global economy and lead to a substantial effect on each country. Therefore, it is vital to understand how large the effect is and how it can be alleviated. However, one major obstacle when we estimate this effect is that trade disruption does not simply affect importers and exporters but the entire economy because of the propagation of the shock through domestic supply chains (Inoue and Todo 2020).

Therefore, this study estimates the effect of the disruption of imports of inputs from various regions on the domestic production of Japan while accounting for supply-chain propagation. Specifically, we simulate an agent-based model on large-scale data on more than one million firms that contain detailed supply chain information and imports and exports at the firm level. Our model and simulations extend those used in the literature that focus on the propagation of economic shocks through domestic supply chains (Inoue and Todo 2020, Inoue and Todo 2019a, Inoue and Todo 2019b, Inoue, Yohsuke, and Todo 2020, Inoue 2021) by incorporating international trade. To the best of the authors' knowledge, this study is the first to simulate the economic effect of the disruption of global supply chains using a model and data at the firm level.

To examine how the sustainability of global supply chains can be strengthened, we further analyse how the network topology of affected nodes, i.e., firms importing intermediate goods, influences the propagation through the network and the total effect. In addition to measures of centrality and density that are often found to be influential in the literature (Kohler, Behrman, and Watkins 2001, Valente 2005), we employ measures of upstreamness of affected nodes and loops in which they are involved as possible determinants of propagation. Finally, we investigate the role of the substitutability of suppliers in sustainability of supply chains.

This study is related and contributes to several strands of literature. First, studies estimate the economic effect of disruptions of global supply chains using theoretical models and industry-level data (Guan et al. 2020, Bonadio, Huo, Levchenko, and Pandalai-Nayar 2021, McKibbin and Fernando 2020). Their major shortcoming is that they use input-output linkages at the country-industry level and ignore complexity of supply chains at the firm level that can aggravate the propagation of economic shocks (Inoue and Todo 2019a, Inoue 2021, Acemoglu, Ozdaglar, and Tahbaz-Salehi 2015, Barabási 2016) and thus are likely to underestimate the economic effect of supply chain disruption (Inoue and Todo 2019a). Therefore, we incorporate firm-level supply chains to more accurately examine the economic effect of supply chain disruption.

Second, several studies adopt an econometric approach to investigate the propagation of economic shocks due to natural disasters on production through supply chains using firm-level data (Barrot and Sauvagnat 2016, Carvalho et al. 2021, Boehm, Flaaen, and Pandalai-Nayar 2019, Kashiwagi, Todo, and Matous 2021). Although this econometric approach can clarify whether and how much a reduction in supply and demand of foreign firms affects the production of each of their supply chain partners, it cannot estimate its total effect on the whole economy. By contrast, our simulation approach enables us to estimate the total effect.

Third, this study contributes to the literature on the relationship between the topology of and propagation through networks. In the literature on the diffusion of information and behaviours through networks, measures of the centrality of each node and the density of its ego-network are often used as determinants of diffusion (Centola 2010, Iyengar, Van den Bulte, and Valente 2011, Kim et al. 2015). In addition to these measures, we examine the effect of unique measures of upstreamness and involvement in loop flows of each affected node that can be calculated using the Helmholtz–Hodge Decomposition (HHD) (Chakraborty et al. 2018, Jiang, Lim, Yao, and Ye 2011, Kichikawa and othres 2019) and find a more important role of upstreamness than that obtained from standard centrality measures.

Finally, our analyses are also related to several studies that investigate how rewiring to or adding new links in response to removal of nodes or links affects the robustness and resilience of connectivity in networks (Chen and Hero 2014, Ganin et al. 2016, Wuellner, Roy, and D'Souza 2010). We find that connecting firms facing supply disruption with new suppliers in network neighbours within a few steps can mitigate the negative effect as much as connecting with new suppliers chosen from the whole network. Our findings suggest that the propagation of economic shocks through supply chains is quite different from diffusion in other types of networks, possibly because of their structure that is based on hierarchy from upstream to downstream but contains many loops in a complex manner (Chakraborty et al. 2018).

2 METHOD

2.1 Data

This study uses two sets of data. The first is the Company Information Database and Company Linkage Database of Tokyo Shoko Research (TSR) for 2020 that contain attributes for most firms in Japan, including small- and medium-sized enterprises (SMEs), and major domestic clients and suppliers of each firm. After dropping firms without sales information, the number of firms and supply-chain links in the sample is 104,9697 and 4,957,967, respectively. Because the TSR data do not contain sales of each firm to final consumers and the transaction volume of each supply chain link, we estimate them using the IO table of Japan in 2015 (Ministry of Internal Affairs and Communications et al. 2015) so that the aggregate transactions between industries and final consumers according to the firm-level estimations match those in the IO table.

The other data source is the Basic Survey of Japanese Business Structure and Activities (*Kigyo Katsudo Kihon Chosa*, hereafter the BSJ) collected annually by the Ministry of Economy, Trade and Industry. The BSJ targets firms in Japan with 50 employees or more and initial capital of 30 million yen or more, i.e., relatively large firms. The response rate of the BSJ in 2019 is 78.8%, and the number of respondent firms was 37,162. The BSJ data include information on imports of inputs from and exports of outputs of firms to broadly classified foreign regions and countries, i.e., Asia, China, Europe, North America, the Middle East, and other regions. Throughout the paper, we follow the definition of regions used in the BSJ data and denote East Asia, including China, Southeast Asia, South Asia, and Central Asia as “Asia” and West Asia as “the Middle East.” We combine the TSR data with trade information at the firm level taken from BSJ data, using firm identification numbers for the BSJ that are also included in the TSR data.

2.2 Model

We extend dynamic agent-based models that focus on domestic supply chains by incorporating imports of inputs and exports of outputs (Inoue and Todo 2020, Inoue and Todo 2019a, Inoue and Todo 2019b, Henriet, Hallegatte, and Tabourier 2012). This subsection and Fig. 1 provide an overview of the model.

The model assumes that firms in a country are linked with each other through domestic supply chains and are also linked with foreign input and output markets through international trade, as illustrated by the arrows in Fig. 1. Each firm utilises a fixed amount of labour and various intermediates provided by its domestic suppliers (for example, Q^{S}_{ij} in the figure) and imported from foreign countries (Q^{IM}_{ia}), produces its product, and sells it to domestic (Q^{S}_{hi}) and foreign client firms (Q^{EX}_{ai}) and final consumers (Q^{S}_{Ci}). Following a Leontief production function, each firm utilises a certain amount of each intermediate good and labour to produce one unit of its product. What and how much intermediate goods are required vary across firms and are determined by the data. Products are sector-specific, and hence, all firms in a particular sector produce the same product. Sectors are defined by the Japan Standard Industrial Classification defined in 2013 (Ministry of International Affairs and Communications 2013) and categorised into 1,460 classifications. Because our data include values of imported inputs from each of broadly defined foreign regions but not product types of the imported inputs, we assume that the sectoral classification of the input imported by a firm is the same as that of the product of the firm. Suppliers and clients are pre-determined by the data and do not change in principle. In other words, even after the disruption of supply chains, firms cannot find any new supplier or client. However, in exercises in the Results and Discussion sections, firms can find other suppliers to

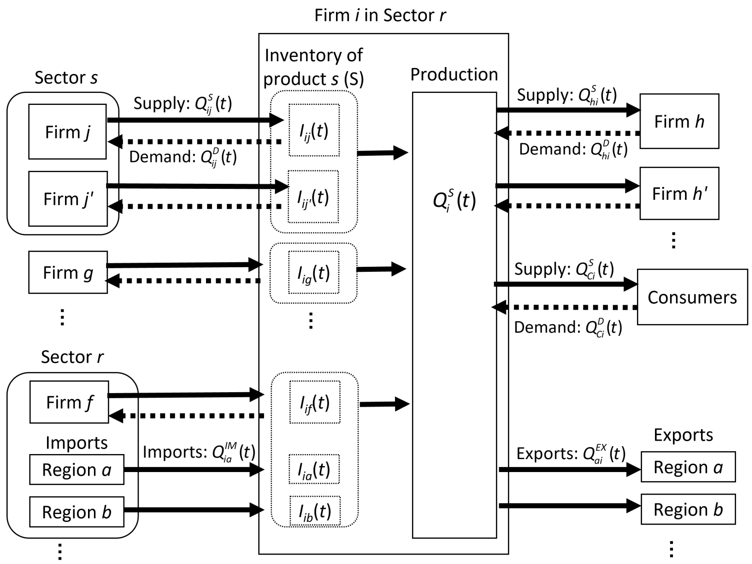

Figure 1: Overview of the agent-based model. Products flow from left to right, whereas orders flow in the opposite direction.

find substitutions. Each firm holds an inventory of intermediates purchased from each manufacturing firm in case of a shortage of supplies (I_{ij}), whereas no inventory is assumed for service inputs. Moreover, when the inventory of intermediates from suppliers in the same sector, for example, firms j and j' in Fig. 1, they are substitutable for each other. In addition, firms hold no inventory of their own product and immediately deliver it to clients and consumers.

We do not assume profit maximisation, following other agent-based models for simplicity. Instead, we assume that each firm follows several rules that determine the demand for each intermediate good and the supply of its product to its clients and consumers. In the initial period, or day 0 without any economic shock, the demand and supply of each firm's product are the same. At day 1, an economic shock, such as policies and natural disasters, disrupts imports from particular foreign regions (Q_{ia}^{IM}). After the shock, firms directly facing disrupted supply chains (firms h and h') reduce production because of supply shortages of inputs. Conversely, disruption of exports to certain regions (Q_{ai}^{EX}) affects exporters' clients (firms j and j'). Furthermore, the shock propagates downstream and upstream to other firms through supply chains. Because of the possible reduction in production, the demand for a firm's product may exceed its supply. If so, the firm determines how its production is allocated to its client firms and consumers following a rationing rule.

2.3 Simulations

Using the agent-based model and firm-level data with supply-chain information, we simulate how the disruption of imports or exports by a trade policy or natural disaster affects the total production of Japan. In particular, we simulate the model using a number of scenarios in five dimensions: (1) the type of trade (imports, exports, or both); (2) the target region (the world, Asia, China, Asia except for China, North America, Europe, the Middle East, and others); (3) the duration of disruption (two, four, or six weeks, or two months); (4) the strength of disruption, i.e., the rate of reduction in imports from or exports to the target region (20, 40, 60, or 80%); and (5) industries of which imports or exports are disrupted (all or one of the manufacturing industries). For example, in one scenario, we assume a reduction in imports of all intermediate products from the world by 60% for four weeks and simulate the total production of Japan day by day. In another, we assume a reduction in imports of electrical machinery, equipment, and supplies from China by 80% for two months.

Then, we calculate the total reduction and the ratio of the reduction in total production because of the disruption to the total production without any disruption during the disruption period, denoted as the reduction rate. In scenarios where we assume disruption in a particular industry, we additionally compute how much the industry-specific disruption reduces the production of the own industry and each of the other industries. By so doing, we can examine spillovers of the effect of industry-specific disruption across industries.

2.4 Helmholtz-Hodge Decomposition

The HHD decomposes a flow in a network into a potential flow component and a loop flow component. A potential flow from a node to another is determined by the upstreamness/downstreamness of the nodes in a network (Jiang, Lim, Yao, and Ye 2011), whereas loop flows are given by the constraint that the summation of the incoming and outgoing loop flows of any node equals zero. This method can be applied to any network to compute potential and loop flows even if a network is complex (Kichikawa and othres 2019, Iyetomi, Aoyama, Fujiwara, Souma, Vodenska, and Yoshikawa 2020, MacKay, Johnson, and Sansom 2020, Fujiwara, Inoue, Yamaguchi, Aoyama, and Tanaka 2020).

2.5 Regressions

In the analysis of the effect of the network topology, we first hypothesise that the number of importers and their centrality in domestic supply chains may positively affect the production loss, as the two are related to the number of nodes affected initially and subsequently. To measure centrality of importers, we use the average of their degree and betweenness centrality.

Second, we hypothesise that if importers are located in more upstream positions, i.e., if they import less assembled material, parts, or components, the effect of import disruption can affect more firms through long supply chains to the bottom and thus result in a larger loss. To compute the upstreamness of each firm, we employ the HHD that is recently applied in network analysis (Jiang, Lim, Yao, and Ye 2011). Using the HHD, we can decompose a flow from a node to another into potential (hierarchical) and loop (horizontal) flows and thus compute the "potential" of each node that can be regarded as a measure of its upstreamness (Chakraborty et al. 2018, Kichikawa and othres 2019). Our firm-level measure of upstreamness can capture heterogeneity in upstreamness across firms within the same industry, unlike industry-level measures of upstreamness often used in the literature (Alfaro et al. 2019, Antràs et al. 2012, Antràs and Chor 2013, Fally and Hillberry 2018). We take the average of the potential of importers in each industry from each region and use it as a measure of the upstreamness of importers.

Finally, we examine how loops affect propagation through supply chains. It is found that supply chains consist of a number of loops in a complex way (Inoue and Todo 2019a, Chakraborty et al. 2018), because upstream suppliers may use final products, such as machinery and computers, produced by downstream assemblers. If an economic shock from import disruption is confined in a loop and does not affect firms outside the loop, the production loss can be smaller than otherwise. Therefore, we hypothesise that the number of loops that pass through importers is negatively correlated with the production loss. Using the HHD, we can compute the number of loop flows in which a node is involved in a network. In addition, we utilise a more widely used measure, the local clustering coefficient of a node that is defined as the ratio of the number of actual links between nodes linked with the focal node to the number of all possible links between them. We use importers' average of the number of loops and the clustering coefficient.

3 RESULTS

3.1 Disruption of imports

Using the method described in detail in the Method section below, we estimate the value of the loss in total value-added production in Japan because of the disruption of imports of inputs from the world or various regions by 20-80% for two, three, four, or six weeks or two months. Throughout the main paper, we focus on disruption of imports because the effect of import disruption is found to be substantially larger than the effect of export disruption. (Inoue and Todo 2022) present the results from disruption of exports to various regions.

Figure 2 depicts the relationship between the duration of import disruption at a particular strength (a reduction in imports by 20-80%) and the loss in value-added production because of the disruption, whereas the inset in the same figure illustrates the relationship between the duration and the ratio of the loss to the total value-added production without disruption in the same period. The following three findings should be emphasized.

First, the effect of import disruption is substantially magnified by the propagation through domestic supply chains. When imports decrease by 80% for two months (60 days), the total value of disrupted imports is 5.9 trillion yen, whereas the reduction in the total value-added production because of the disruption is 41.1 trillion yen, or approximately 7 times as large as the disrupted imports (Fig. 2). The loss in value added because of the import disruption accounts for 47.5% of total value-added production (the inset).

Second, the loss in value-added production is not proportional to the duration of import disruption. Disruption at any strength level for two weeks causes a negligible reduction in value-added production, because firms are assumed to hold inventories of intermediates for the amount of nine days of their use on average ((Inoue and Todo 2022)). However, the reduction rate becomes non-negligible four weeks after the start of the disruption when its strength is high: 7.2 and 18.1% because of a reduction in imports by 60 and 80%, respectively. When the disruption lasts for two months, i.e., an approximately doubled duration, the corresponding reduction rate becomes far larger: 29.0 (4.0 times) and 47.5% (2.6 times). This exponential growth of the reduction in production is due to propagation of the effect of disruption of imports to direct and indirect clients of importers through supply chains.

Finally, as the strength of disruption increases, the loss in value-added production also increases exponentially, rather than proportionally. When the level of a 2-month disruption doubles from 40 to 80%, the production loss becomes more than 4 times from 10.0 trillion yen (11.5% of the total value added for the 2 months) to 41.1 trillion yen (47.5%). This finding implies that a small difference in the initial shock is enhanced substantially in the long run.

3.2 The effect of network topology on propagation

We estimate how the average network topology of importers, such as degree and betweenness centrality, upstreamness in supply chains measured by “potential”, the number of loops involved, and the local clustering coefficients, affects the size of the production loss, using a regression framework (see the Method section for details). Potential and the number of loops are computed from the HDD (Method). The estimated coefficient of each variable and its 95% confidence interval are shown in Fig. 3. The blue, orange, and green dots and lines indicate results from disruption of imports for 4 weeks, 6 weeks, and 2 months, respectively.

We find that when imports from a region are disrupted, the number of importers has a positive and significant effect on the loss of value-added production because of import disruption regardless of the duration of

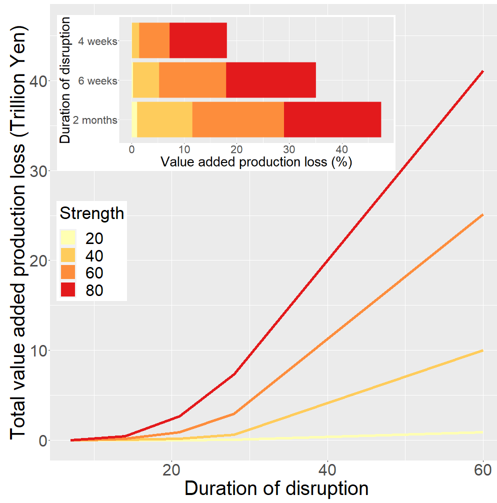

Figure 2: The effect of disruption of imports from the world on the domestic production. The main panels in the figure show the total loss of value-added production in Japan when imports from the world are disrupted to a particular strength (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panels show the rate of the loss in value-added production to the total production when imports from and exports to the world are disrupted at particular strength for 4 and 6 weeks, and 2 months. Note that the right edge of each colour of the bars indicates the loss rate at the corresponding strength (20, 40, 60, or 80%).

disruption. The values of the significant coefficients imply that an increase in the number of importers by one standard deviation is associated with a substantial increase in production loss by 80-94%.

However, the effect of some other variables varies depending on the duration of import disruption. The outdegree, or the number of clients of importers, positively affects the production loss when the duration is 4 weeks, and the effect is large because an increase in the outdegree by one standard deviation raises the production loss by 70%. However, the effect of outdegree is smaller and statistically insignificant when the duration is longer than 4 weeks. Similarly, the measure of loop flows is negatively correlated with the production loss, but the correlation is statistically significant only when the duration is 4 weeks. By contrast, the effect of potential, a measure of upstreamness, is insignificant when the duration is 4 weeks, while it becomes positive and significant when the duration is 6 weeks or 2 months. An increase in potential by one standard deviation leads to an increase in production loss in 2 months by 62%.

These results imply that in the short run, the outdegree of importers and their involvement in loop flows substantially affects the production loss, most likely because a higher outdegree results in immediate propagation to a large number of firms and because the presence of loops helps confine the shock in the loops. However, in the long run, shocks propagate to more downstream indirect clients of importers beyond their direct clients and cannot be confined within loops of importers but escape outside. Therefore, the upstreamness of importers plays a more important role in propagation in the long run than their outdegree and involvement in loops.

Furthermore, we find that the indegree, betweenness centrality, or clustering coefficient of importers has no significant effect using any duration, once we control for the number of importers and thus use the average values of importers. These findings suggest that standard measures of network topology often used in the literature may not be good predictors of the long-run propagation of shocks through supply chains, whereas the upstreamness of affected nodes, which has not been well examined, generally plays a larger role. This finding implies that the key factors of propagation in supply chains are different from those in other standard networks because of the crucial role of upstreamness/downstreamness in supply chains.

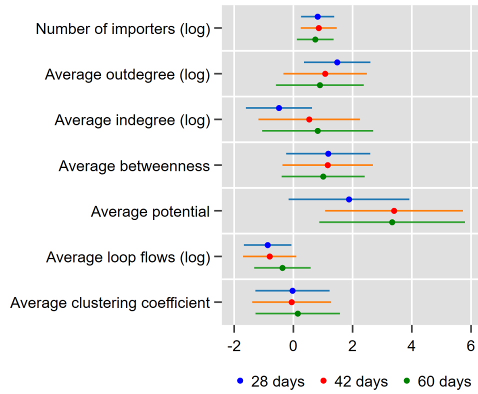

Figure 3: The effects of the network topology of importers on the production loss. This figure shows coefficients and their 95% confidence intervals from three regressions of the decline in production in logs because of disruption of imports from a particular region to a particular manufacturing industry for 4 weeks, 6 weeks, or 2 months. In each regression, we control for the value of disrupted imports in logs. To make the sizes of coefficients comparable across variables, we multiply the average clustering coefficient by 10 and the average betweenness by 10,000.

3.3 Substitution of suppliers

Given that the negative effect of import disruption is found to be magnified by domestic supply chains, the next question is how we can mitigate the propagation. We particularly examine the role of substitution among domestic suppliers suggested in the literature (Barrot and Sauvagnat 2016) by simulating three modified models assuming different levels of substitution.

In our benchmark model, after import disruption, firms cannot be linked with suppliers or clients without any prior link to cope with supply chain disruption. However, in the first modified model, we assume that when a client firm faces a reduction in the transaction volume with one of its suppliers, it can be matched with another supplier in Japan and procure disrupted supplies from the new supplier as long as the new supplier has production capacity. Because this matching assumption may be too strong from a practical perspective, our second modified model alternatively assumes that a client firm facing supply disruption can find another supplier that was not directly linked but indirectly linked through supply chains within two steps. For example, the inset of Fig. 4 shows that firm D is indirectly linked with supplier C through B and E, and suppose that A and C are in the same industry. Then, when the transactions between A and D declines after a shock, we assume that firm D may procure its supplies from C depending on the production capacity of C, because information about firm C flows through supply chains to D. Such endogenous network shifts based on the current network are empirically found in the literature (Uzzi 1996, Matous and Todo 2017). Finally, to highlight the importance of supplier substitution, we also experiment with another model that assumes no substitution between suppliers even when suppliers are in the same industry.

Fig. 4 shows changes in daily value-added production in Japan for 60 days predicted by the four models, assuming a disruption of 80% of imports from the world. The green, red, blue, and brown lines in the figure indicate the results assuming no substitutability of suppliers, substitutability between current suppliers (the benchmark case), substitutability between network neighbours, and complete substitutability, respectively. Although daily value added 2 months after the start of import disruption is similar across the 4 scenarios, it varies substantially up to 4 weeks. Accordingly, the cumulative production loss in value added for the first 4 weeks is 13.5% of total value added without disruption under the substitutability of neighbouring suppliers, while it is 18.1% in the benchmark case. Moreover, using the alternative models assuming the no substitutability and complete substitutability, the cumulative production decreases by 27.5 and 12.2%, respectively.

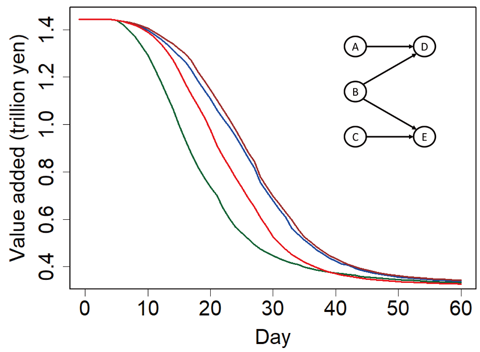

Figure 4: Production decrease because of import disruption using different assumptions on substitution of suppliers. This figure illustrates changes in daily total value added after the disruption of imports from the world by 80% for 60 days. The green, red, brown, and blue lines indicate changes assuming no supplier substitution, substitution between current suppliers in the same industry, perfect substitution with new suppliers, and substitution with new suppliers indirectly linked through supply chains, respectively. The inset panel illustrates how firms find new suppliers after supply chain disruption in an alternative model.

These results clearly suggest that the negative effect of import disruption can be mitigated by more flexible reorganisation of domestic supply chains. In addition, we find that matching with new suppliers indirectly linked through supply chains only a few steps away leads to a production decline similar to that when assuming complete matching with any supplier. This finding implies that the reorganisation of supply chains only within neighbouring firms can substantially ameliorate the negative effect of import disruption.

4 DISCUSSIONS

Some of our findings are unique in the literature on network science. First, we find that although the extent of the propagation of the effect of import disruption through the supply-chain network is positively affected by the degree centrality of affected nodes in the short run, the effect of the degree or any standard centrality measure disappears in the long run, once we control for the number of affected nodes. Our results contrast to others that find that the centrality of nodes is a major determinant of diffusion of information and behaviour from the nodes (Iyengar, Van den Bulte, and Valente 2011, Kim et al. 2015). By contrast, our findings indicate that the upstreamness of affected nodes is positively correlated with the long-run propagation effect, most likely because an economic shock from a more upstream position propagates through long supply chains to the bottom and thus affects more firms in the long run.

Second, loops in supply chains are found to alleviate propagation in the short run, although some studies find that clusters can promote diffusion of behaviour because of reinforcement from clustered neighbours (Centola 2010). We obtain results different from the previous work because when affected nodes are involved in many loops and clusters in supply chains, the shock may be confined to the loops and may not extensively affect the economy outside them in the short run.

Finally, our experiments reveal that substitution between only neighbouring nodes indirectly linked a few steps apart in the network can mitigate propagation of the negative effect as much as substitution between distant nodes. Although the importance of supplier substitution for sustainable supply chains has been empirically found in several previous studies (Inoue and Todo 2019a, Inoue and Todo 2019b, Barrot and Sauvagnat 2016, Kashiwagi, Todo, and Matous 2021), they do not compare different types of substitution for higher sustainability. Some studies in network science examine how rewiring of nodes improves sustainability in the context of airline and power grid networks (Chen and Hero 2014, Wuellner, Roy, and D'Souza 2010), but they do not show that rewiring between network neighbours can effectively improve sustainability.

These findings provide policy and managerial implications for sustainable global supply chains and global economy. First, our finding on the role of the network topology of importers implies that to minimise the economic effect of policies that restrict imports from a particular country, policy makers should be concerned about the structure of supply chains, rather than simply focusing on the value of restricted imports. Second, firms' inventories of intermediate goods for a longer time can alleviate the negative effect of supply chain disruption. Finally, firms are encouraged to plan for possible substitution of neighbouring suppliers in supply chains for affected suppliers in the event of supply chain disruption.

REFERENCES

Acemoglu, D., A. Ozdaglar, and A. Tahbaz-Salehi. 2015. "Systemic risk and stability in financial networks". *The American Economic Review* vol. 105 (2), pp. 564–608.

Alfaro, L. et al. 2019. "Internalizing global value chains: A firm-level analysis". *Journal of Political Economy* vol. 127 (2), pp. 508–559.

Antràs, P. et al. 2012. "Measuring the upstreamness of production and trade flows". *The American Economic Review* vol. 102 (3), pp. 412–416.

Antràs, P., and D. Chor. 2013. "Organizing the global value chain". *Econometrica* vol. 81 (6), pp. 2127–2204.

Baldwin, R. 2016. *The Great Convergence: Information Technology and the New Globalization*. Boston, Harvard University Press.

Barabási, A.-L. 2016. *Network science*. Cambridge University Press.

Barrot, J.-N., and J. Sauvagnat. 2016. "Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks". *The Quarterly Journal of Economics* vol. 131 (3), pp. 1543–1592.

Boehm, C. E., A. Flaaen, and N. Pandalai-Nayar. 2019. "Input linkages and the transmission of shocks: Firm-level evidence from the 2011 Tōhoku earthquake". *Review of Economics and Statistics* vol. 101 (1), pp. 60–75.

Bonadio, B., Z. Huo, A. A. Levchenko, and N. Pandalai-Nayar. 2021. "Global supply chains in the pandemic". *Journal of international economics* vol. 133, pp. 103534.

Carvalho, V. M. et al. 2021. "Supply chain disruptions: Evidence from the Great East Japan earthquake". *Quarterly Journal of Economics* vol. 136 (2), pp. 1255–1321.

Centola, D. 2010. "The Spread of Behavior in an Online Social Network Experiment". *Science* vol. 329 (5996), pp. 1194–1197.

Chakraborty, A. et al. 2018. "Hierarchical communities in the walnut structure of the Japanese production network". *PloS one* vol. 13 (8).

Chen, P.-Y., and A. O. Hero. 2014. "Assessing and safeguarding network resilience to nodal attacks". *IEEE Communications Magazine* vol. 52 (11), pp. 138–143.

Fally, T., and R. Hillberry. 2018. "A Coasian model of international production chains". *Journal of International Economics* vol. 114, pp. 299–315.

Farrell, H., and A. L. Newman. 2022. “Weak links in finance and supply chains are easily weaponized”. *Nature* vol. 605, pp. 219–222.

Friedt, F. L., and K. Zhang. 2020. “The triple effect of Covid-19 on Chinese exports: First evidence of the export supply, import demand and GVC contagion effects”. *Covid Economics* vol. 53, pp. 72–109.

Y. Fujiwara and H. Inoue and T. Yamaguchi and H. Aoyama and T. Tanaka 2020, July. “Money Flow Network Among Firms’ Accounts in a Regional Bank of Japan”. https://ssrn.com/abstract=3662893.

Fuller, D. B. 2022. “Weaponizing Interdependence & Global Value Chains: US Export Controls on Huawei”. *American Political Science Association pre-prints, Available at SSRN: https://ssrn.com/abstract=4221915*.

Ganin, A. A. et al. 2016. “Operational resilience: concepts, design and analysis”. *Scientific Reports* vol. 6 (1), pp. 1–12.

Guan, D. et al. 2020. “Global economic footprint of the COVID-19 pandemic”. *Nature Human Behavior* vol. 4, pp. 577–587.

Henriet, F., S. Hallegatte, and L. Tabourier. 2012. “Firm-network characteristics and economic robustness to natural disasters”. *Journal of Economic Dynamics and Control* vol. 36 (1), pp. 150–167.

Inoue, H. 2021. “Propagation of International Supply-Chain Disruptions between Firms in a Country”. *Journal of Risk and Financial Management* vol. 14 (10), pp. 461.

Inoue, H., and Y. Todo. 2019a. “Firm-level propagation of shocks through supply-chain networks”. *Nature Sustainability* vol. 2, pp. 841–847.

Inoue, H., and Y. Todo. 2019b. “Propagation of Negative Shocks through Firm Networks: Evidence from Simulation on Comprehensive Supply-Chain Data”. *PLoS ONE* vol. 14 (3).

Inoue, H., and Y. Todo. 2020. “The propagation of economic impacts through supply chains: The case of a mega-city lockdown to prevent the spread of COVID-19”. *PloS one* vol. 15 (9), pp. e0239251.

Inoue, H., and Y. Todo. 2022. “Propagation of overseas economic shocks through global supply chains: Firm-level evidence”. *RIETI Discussion Paper Series*.

Inoue, H., M. Yohsuke, and Y. Todo. 2020. “Do economic effects of the anti-COVID-19 lockdowns in different regions interact through supply chains?”. *arXiv preprint*. arXiv:2009.06894.

Iyengar, R., C. Van den Bulte, and T. W. Valente. 2011. “Opinion leadership and social contagion in new product diffusion”. *Marketing science* vol. 30 (2), pp. 195–212.

Iyetomi, H., H. Aoyama, Y. Fujiwara, W. Souma, I. Vodenska, and H. Yoshikawa. 2020. “Relationship between Macroeconomic Indicators and Economic Cycles in U.S.”. *Sci. Rep.* vol. 10, pp. 8420. https://doi.org/10.1038/s41598-020-65002-3.

Jiang, X., L.-H. Lim, Y. Yao, and Y. Ye. 2011. “Statistical Ranking and Combinatorial Hodge Theory”. *Mathematical Programming* vol. 127 (1), pp. 203–244.

Kashiwagi, Y., Y. Todo, and P. Matous. 2021. “Propagation of economic shocks through global supply chains: Evidence from Hurricane Sandy”. *Review of International Economics* vol. 29 (5), pp. 1186–1220.

Kichikawa, Y., and othres. 2019. “Community structure based on circular flow in a large-scale transaction network”. *Applied Network Science* vol. 4 (1), pp. 92.

Kilpatrick,Jim 2022. “Supply chain implications of the Russia-Ukraine conflict”. Deloitte Insights, https://www2.deloitte.com/xe/en/insights/focus/supply-chain/supply-chain-war-russia-ukraine.html. Accessed Apr. 20, 2022.

Kim, D. A. et al. 2015. "Social network targeting to maximise population behaviour change: a cluster randomised controlled trial". *The Lancet* vol. 386 (9989), pp. 145–153.

Kohler, H.-P., J. R. Behrman, and S. C. Watkins. 2001. "The density of social networks and fertility decisions: Evidence from South Nyanza District, Kenya". *Demography* vol. 38 (1), pp. 43–58.

MacKay, R., S. Johnson, and B. Sansom. 2020. "How directed is a directed network?". *arXiv preprint arXiv:2001.05173*.

Matous, P., and Y. Todo. 2017. "Analyzing the coevolution of interorganizational networks and organizational performance: Automakers' production networks in Japan". *Applied Network Science* vol. 2 (1), pp. 5.

McKibbin, Warwick J and Fernando, Roshen 2020. "The global macroeconomic impacts of COVID-19: Seven scenarios". CAMA Working Paper, No. 19/2020, Crawford School of Public Policy, Australian National University.

Meier, M., and E. Pinto. 2020. "Covid-19 supply chain disruptions". *Covid Economics* vol. 48, pp. 139–170.

Ministry of Internal Affairs and Communications and others 2015. "2015 Input-Output Tables for Japan". https://www.soumu.go.jp/english/dgpp_ss/data/io/index.htm.

Ministry of International Affairs and Communications 2013. *Japan Standard Industrial Classification (Revision 13)*. Accessed Apr. 19, 2022.

Todo, Yasuyuki 2022. "Toward More Resilient and Innovative Supply Chains". Monograph, the S. Rajaratnam School of International Studies, Nangyang Technological University, Singapore.

Uzzi, B. 1996. "The sources and consequences of embeddedness for the economic performance of organizations: The network effect". *American Sociological Review* vol. 61 (4), pp. 674–698.

Valente, T. W. 2005. "Network models and methods for studying the diffusion of innovations". *Models and methods in social network analysis* vol. 28, pp. 98–116.

Wuellner, D. R., S. Roy, and R. M. D'Souza. 2010. "Resilience and rewiring of the passenger airline networks in the United States". *Physical Review E* vol. 82 (5), pp. 056101.

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