Firm-level Propagation of the Effect of the Disruption of International Trade through Domestic Supply Chains

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Abstract

The risk of disruption to global supply chains is rising because of the increasing frequency of pandemics and natural disasters and deteriorating geopolitical stability, threatening the sustainability of global supply chains. This study simulates how the disruption of imports from various regions affects 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 the 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 the reorganisation of domestic supply chains, even when conducted only among network neighbours. Our findings highlight the differences between the propagation of economic effects through supply chains and the diffusion of information and behaviours through social networks and provide important policy and managerial implications for the achievement of more sustainable global supply chains.

Keywords: Global supply chains; trade disruption; simulation.

Introduction

The 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) [1, 2, 3]; natural disasters, such as the Great East Japan earthquake [4, 5]; military conflicts, such as the Russo-Ukrainian War [6]; and policies among the United States and its allies to "decouple" themselves from China [7]. The risk of the disruption of global supply chains has been rising because pandemics and natural disasters are predicted to occur more frequently in the future due to climate change and seismic cycles [8, 9, 10, 11, 12]. In addition, this disruption risk has been intensified because of increasing possibilities of countries "weaponising" supply chains by restricting trade with particular partners for national security reasons as global geopolitical risks soar [13, 14].

Global supply chains contribute to economic efficiency by allocating production processes across countries depending on their advantages and thus benefit both developed economies, which are the hubs of supply chains, and developing economies, which have only recently started to participate in supply chains [15]. Therefore, the possible disruption of global supply chains on a large scale would jeopardise the sustainability of the global economy and thus have a substantial effect on all involved countries. Therefore, it is vital to understand how large the effect is and how it can be alleviated. However, one major obstacle

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when estimating this effect is that trade disruption affects not only importers and exporters but also the entire economy because of the propagation of the shock through domestic supply chains [16].

Therefore, this study estimates the effect of the disruption of the 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 with 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 [16, 17, 18, 19, 20] by incorporating international trade. To the best of our 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 propagation through the network and the total effect. In addition to measures of centrality and density, which have often been found to be influential in the literature [21, 22], we employ measures of the upstreamness of affected nodes and the loops in which they are involved as possible determinants of propagation. Finally, we investigate the role of the substitutability of suppliers in the sustainability of supply chains.

This study is related and contributes to several strands of literature. First, some studies estimate the economic effect of disruptions to global supply chains using theoretical models and industry-level data [2, 23, 24]. However, their major shortcoming is that they use input–output (IO) linkages at the country-industry level and ignore the complexity of supply chains at the firm level, which can aggravate the propagation of economic shocks [17, 20, 25, 26]; thus, such studies likely underestimate the economic effect of supply chain disruption [17]. 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 effect of the propagation of economic shocks due to natural disasters on production through supply chains using firm-level data [4, 5, 27, 28]. Although this econometric approach can clarify whether and to what degree a reduction in the supply and demand of foreign firms affects the production of each of their supply chain partners, it cannot estimate the total effect of such a reduction on the whole economy . In contrast, our simulation approach enables us to estimate this 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 [29, 30, 31]. In addition to these measures, we examine the effective measures of upstreamness in potential flows and involvement in loop flows of each affected node, which can be calculated using Helmholtz–Hodge decomposition (HHD) [32, 33, 34], and find a more important role of upstreamness than that obtained through the use of standard centrality measures. The propagation of economic shocks through supply chains is quite different from diffusion in other types of networks, possibly because of their structure, which is based on hierarchy from upstream to downstream but contains many loops in a complex manner [32].

Finally, our analyses are also related to several studies that investigate how rewiring or adding new links in response to the removal of nodes or links affects the robustness and resilience of network connectivity [35, 36, 37]. We find that connecting firms facing supply disruption with new suppliers in network neighbours, such as suppliers of competitive firms in ordinary times, can mitigate the negative effect as much as can connecting with new suppliers chosen from the whole network. Our findings suggest that since competitive firms can be easily recognised in ordinary times, resilience can be achieved through a cooperative framework during emergency situations between competitive firms, which is quite useful.

Results

Import disruption

Using the method described in detail in the Method section, we estimate the value of the loss in total value-added production in Japan due to the disruption of the imports of inputs from the world or from various regions by 20-80% for two, four, or six weeks or two months. Throughout the main paper, we focus on the disruption of imports because the effect of import disruption is found to be substantially larger than is the effect of export disruption. The Results section in the Supplementary Information (SI) file presents the results from the disruption of exports to various regions and the disruption of imports and outputs.

Fig. 1 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 due to this disruption, whereas the inset in the same figure illustrates the relationship between the duration and ratio of loss to total value-added production without disruption in the same periods. Since the results for two weeks are almost negligible, they are not shown. Furthermore, the three findings presented below should be emphasised.

First, the effect of import disruption is substantially magnified by 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 due to this disruption is 41.1 trillion yen, or approximately 7 times as large as that for disrupted imports (Fig. 1). The loss in value added due to import disruption accounts for 47.5% of total value-added production (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 nine days of their use on average (Model section in the SI file). However, the reduction rate becomes nonnegligible four weeks after the start of the disruption when its strength is high: 7.2 and 18.1% due to 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 the disruption of imports to the 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 4 times as large, from 10.0 trillion yen (11.5% of the total value added for the 2 months) to 41.1 trillion yen (47.5%). This result is due to the cascading effect of supply chain disruptions. If the shock is relatively small, then it can be absorbed by substitutability. However, if the shock is large, then it cannot be absorbed and causes a cascading effect. Therefore, a small difference in the initial shock can be substantially enhanced in the long run.

Fig. 2 depicts the simulation results assuming the disruption of imports from various regions that are defined by our data: China, Asia except for China (other Asia), North America, and Europe. Our data also include the Middle East and other areas as partner regions, but the results are not shown here for simplicity (see the SI file). The results in all panels share the same characteristics as the abovementioned simulation of the disruption of global imports: exponential growth in the reduction rate in production as the duration or level of disruption increases. Comparing the panels, we observe that the largest effect comes from the disruption of imports from China, followed by those from other Asia. The disruption of imports from China and other Asia for two months by 80% reduces total value-added production by 14.8 and 14.3%, respectively. This large effect for Asia is obviously due to its large share of imports of intermediate goods to Japan.

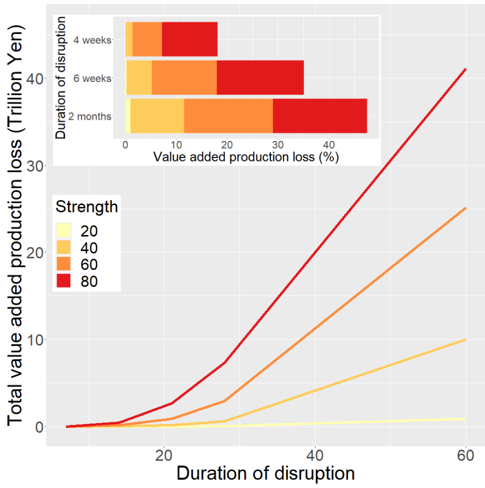

Figure 1: **The effect of the disruption of global imports on domestic production.** The main panels in the figure show the total loss of value-added production in Japan when global imports are disrupted at a particular strength (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panels show the ratio of the loss in value-added production to the total production when global imports are disrupted at a 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%).

Industry-level analysis

We now perform industry-by-industry analysis. Specifically, we investigate how a reduction in imports in a particular manufacturing industry by 80% for six weeks affects production in other industries. Those industries for which imports are disrupted are limited to manufacturing industries and defined at the two-digit level according to the Japan Standard Industrial Classification [38]. Those industries that are affected by such disruption are defined at the one-digit level for nonmanufacturing industries and at the two-digit level for manufacturing industries (SI Tables 1 and 2).

The results are presented in Fig. 3. The upper-left panel shows the effect of the disruption of global imports to a particular industry, in the horizontal axis, on various industries, on the vertical axis. Several findings are notable. First, the disruption of manufacturing imports (industries E09-E32) substantially reduces production in most manufacturing sectors, while its effect on nonmanufacturing sectors (A-D and F-T), except for the mining industry (C), is limited. Second, among manufacturing industries (E), the disruption of imports in most light industries, such as the food and beverage industry (9-10), wood and furniture industry (12-13), paper industry (14), and leather industry (20), does not largely affect other manufacturing industries. In contrast, when a heavy or high-tech manufacturing industry (15-32 except for 20) is affected, the effect propagates to other industries.

We focus on the disruption of imports from selected regions, i.e., China, other Asia, and North America, in the other panels of Fig. 3. The comparison among the three panels clearly shows that the effect of the disruption of imports from China and other Asia to any industry is far greater than that from North America. In addition, the disruption of imports from China and other Asia results in similar patterns of interindustry propagation. Notably, interindustry propagation is more prominent when imports to industries, such as the chemical (code E16), plastic (18), production machinery (26), business machinery (27), electronics (28), electrical machinery and equipment (29), and information and communication electronics equipment (30) industries, are disrupted.

Fig. 4 further shows the relationship between the value of disrupted imports to a particular industry from each region and the production loss in the whole economy due to import disruption. In Fig. 4, the light-to-dark-red dots represent import disruptions from China, whereas the light-to-dark-blue dots represent those from other Asia. The numbers next to selected dots indicate industry classification codes. We find that the top industries in terms of the effect of the disruption of imports from China and other Asia include the electrical machinery and electronics (28-30), plastic (18), chemical (16), and machinery

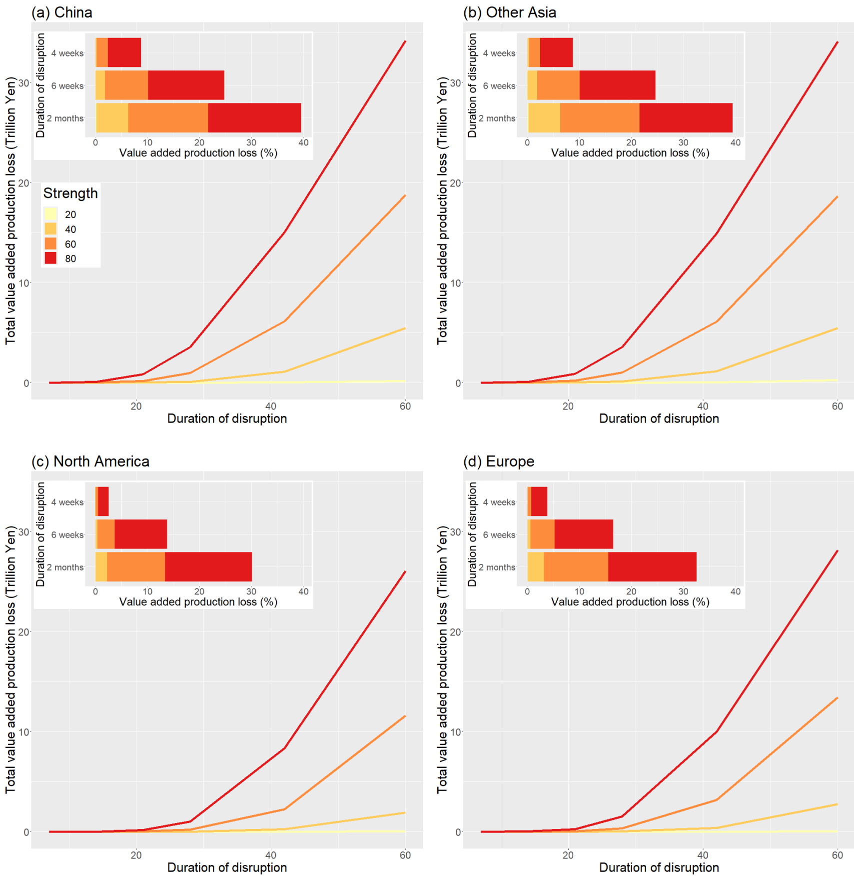

Figure 2: **The effect of the disruption of imports from various areas on domestic production.** The main panels in the figure show the total loss in value-added production in Japan when imports from each region are disrupted to a particular extent (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panels show the ratio of the loss in value-added production to total production when the imports from each region are disrupted at a particular strength for 4 and 6 weeks and 2 months. The right edge of each colour of the bars indicates the loss rate at the corresponding strength (20, 40, 60, or 80%). "Other Asia" represents Asian countries except for China.

(26-27) industries. These findings suggest that the disruption of imports, particularly from China and other Asia, to selected industries, most notably the electrical machinery and equipment industry, will reduce production not only in these industries but also in the whole Japanese economy via the propagation of economic shocks through supply chains.

Another notable finding from Fig. 4 is that the production loss is not necessarily proportional to the value of disrupted imports. For example, the disruption of imports from China or other Asia to the plastic (18) and metal products industries would cause a large production loss, although their volumes of disrupted imports are small. Therefore, we now turn to how the production loss propagates through supply chains, focusing on the role of the network topology of importers.

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). The potential and number of loops are computed by HHD (see the Method section). The estimated coefficient of each variable and its 95% confidence interval are shown in Fig. 5. The blue, orange, and green dots and lines indicate results from the disruption of imports for 4 weeks, 6 weeks, and

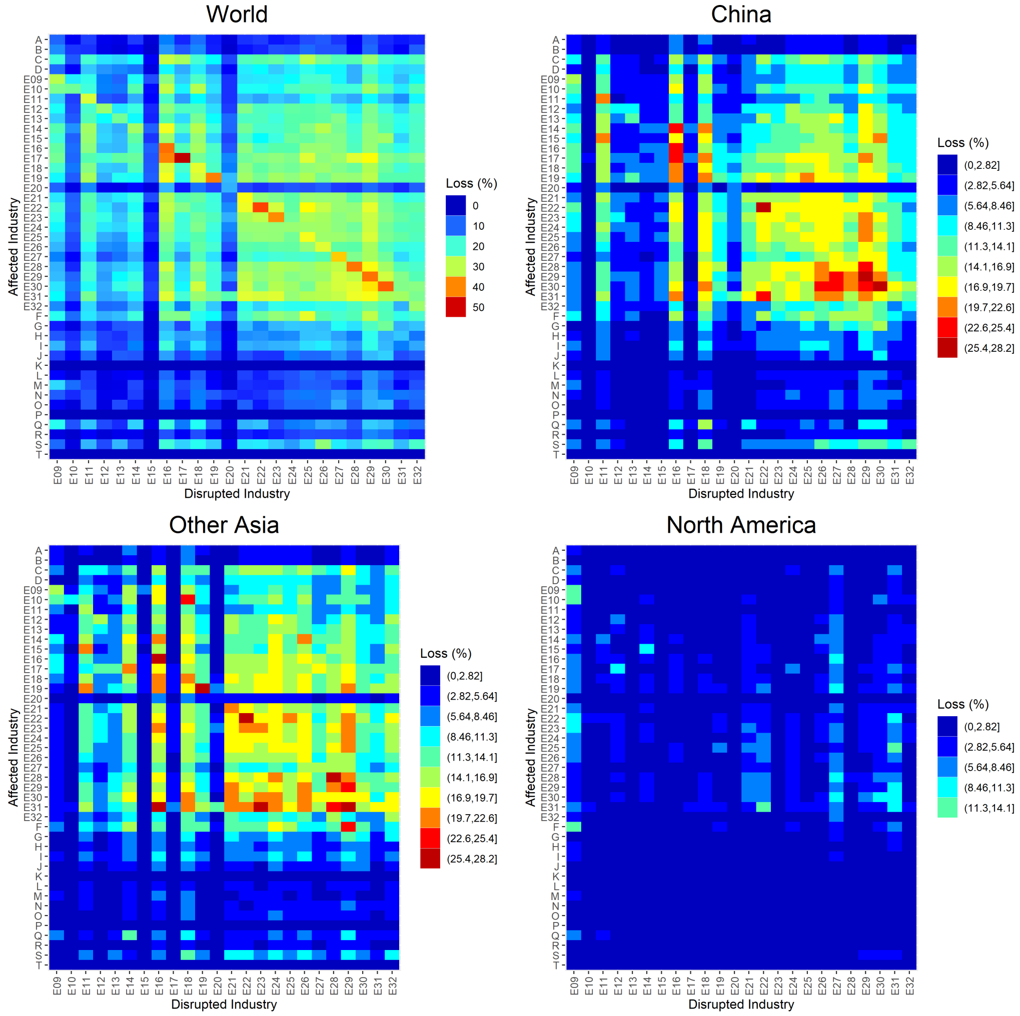

Figure 3: **The effect of import disruption on production by industry and exporter country.** The heat maps show the ratio of loss in the value-added production of each industry, on the vertical axis, to its total production when imports to a particular industry, on the horizontal axis, from a particular region, labelled at the top of each panel, are disrupted by 80% for 6 weeks. Those industries on the horizontal axis (disrupted industries) are at the two-digit level in the manufacturing sector, whereas those industries on the vertical axis (affected industries) are at the one-digit level for nonmanufacturing industries and at the two-digit level for manufacturing industries. The colour separations in the panel labelled "World" are defined independently, whereas those in the other panels are commonly defined.

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 due to import disruption, regardless of the duration of such 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 production loss when the duration is 4 weeks; this effect is large because an increase in the outdegree by one standard deviation raises production loss by 70%. However, the effect of the outdegree is smaller and nonsignificant when the duration is longer than 4 weeks. Similarly, the measure of loop flows is negatively correlated with production loss, but the correlation is significant only when the duration is 4 weeks. In contrast, the effect of potential, a measure of upstreamness, is nonsignificant when the duration is 4 weeks but becomes positive and significant when the duration is 6 weeks or 2 months. Furthermore, an increase in potential by one standard deviation

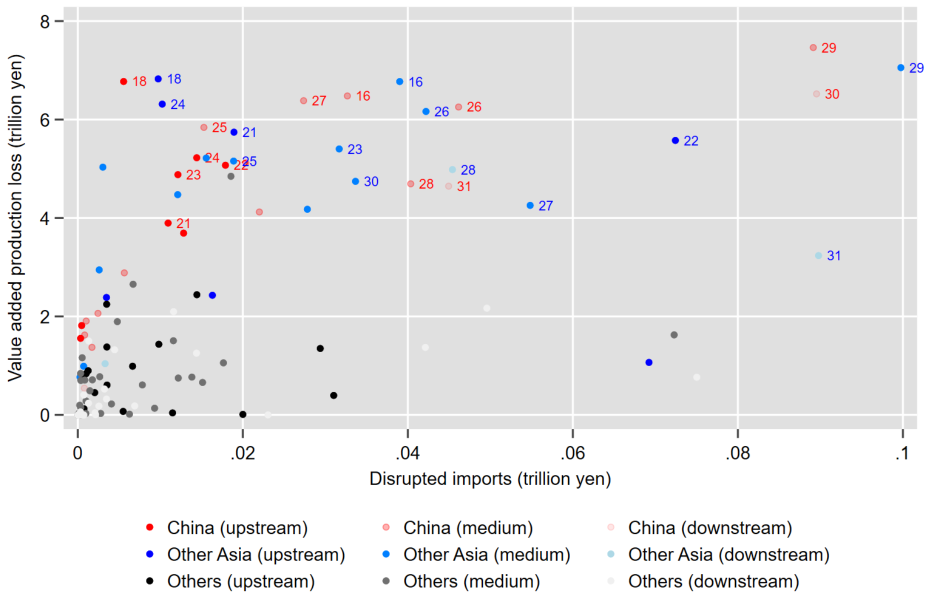

Figure 4: **Relationship between disrupted imports and the resulting production loss by industry.** This figure shows the correlation between a reduction in imports of a particular industry in the manufacturing sector from each region by 80% for 6 weeks and the reduction in production due to import disruptions (both in trillions of yen). The red, blue, and black dots, including their light-coloured versions, indicate imports from China, other Asia, and other regions except for Asia, respectively. The darkness of the colour indicates the upstreamness of importers in supply chains. The definition of upstreamness is given in the Results section. The numbers next to the selected dots indicate their industry classification. The classification codes are explained in detail in SI Table 2.

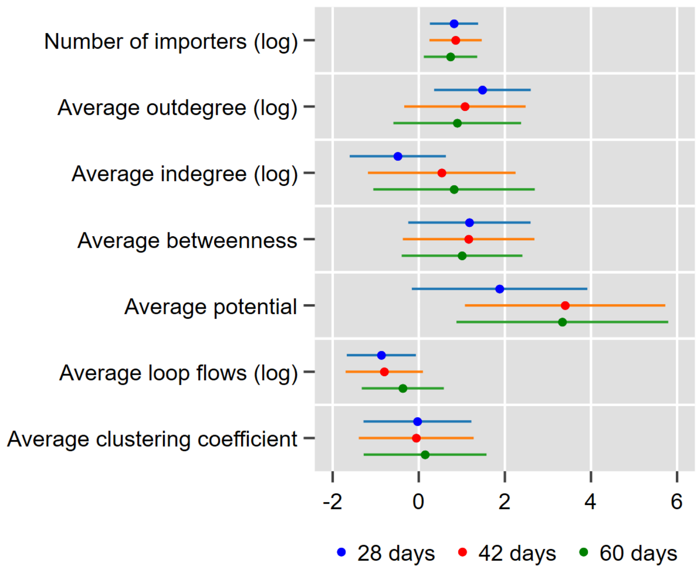

Figure 5: **The effects of the network topology of importers on production loss.** This figure shows coefficients and their 95% confidence intervals from three regressions of the decline in production in logs because of the disruption of imports from a particular region to a particular manufacturing 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 average betweenness by 10,000.

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 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 to 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 rather escape outside. Therefore, the upstreamness of importers plays a more important role in propagation in the long run than do 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.

Substitution of suppliers

Given that the negative effect of import disruption is found to be magnified by domestic supply chains, the next question aims to address how propagation can be mitigated. We particularly examine the role of substitution among domestic suppliers suggested in the literature [4] 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 the appropriate 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 not directly but indirectly linked through supply chains within two steps. The inset of Fig. 6 indicates how the new supplier is found. Firm D is indirectly linked with supplier C through B and E. Let us suppose that A and C are in the same industry. Then, when the transactions between A and D decline after a shock, we assume that firm D procures its supplies from C depending on the production capacity of C because information about firm C flows through supply chains to firm D. Such endogenous network shifts based on the current network are empirically found in the literature [39, 40]. In addition, this model includes a case where competitive firms share suppliers. Finally, to highlight the importance of supplier substitution, we also experiment with another model that assumes no substitution between suppliers, even when they are in the same industry.

Fig. 6 shows the changes in daily value-added production in Japan for 60 days predicted by the four models, assuming a disruption of 80% of global imports. The green, red, blue, and brown lines in the figure indicate the results assuming no substitutability of suppliers, substitutability between current suppliers (benchmark case), substitutability between network neighbours, and complete substitutability, respectively. Although the daily value added 2 months after the start of import disruption is similar across the 4 scenarios, it varies substantially up until 4 weeks. Accordingly, the cumulative value-added production loss for the first 4 weeks is 13.5% of total value added without disruption under the substitutability of neighbouring suppliers while 18.1% in the benchmark case. Moreover, using alternative models assuming both no substitutability and complete substitutability, cumulative production is shown to decrease by 27.5 and 12.2%, respectively.

These results clearly suggest that the negative effect of import disruption can be mitigated by a more flexible reorganisation of domestic supply chains. In addition, we find that matching with new suppliers

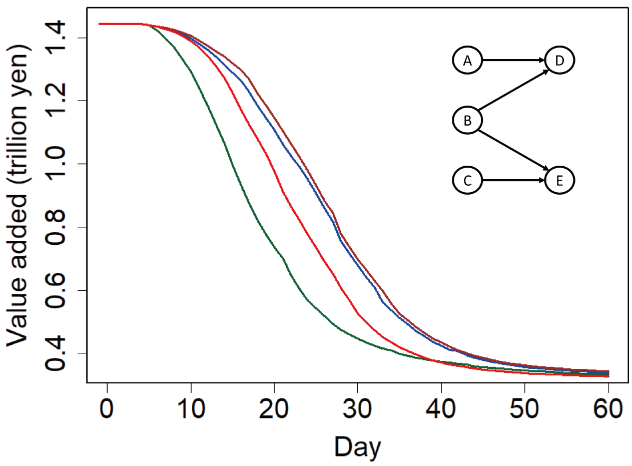

Figure 6: **Decrease in production due to import disruption using different assumptions regarding supplier substitution.** This figure illustrates the changes in daily total value added after the disruption of global imports by 80% for 60 days. The green, red, blue, and brown lines indicate changes assuming no supplier substitution, substitution between current suppliers in the same industry, substitution with new suppliers indirectly linked through supply chains, and perfect substitution with new suppliers, respectively. The inset panel illustrates how firms find new suppliers after supply chain disruption in the alternative model.

indirectly linked through supply chains only a few steps away leads to a decline in production 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.

Discussion

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 with other results showing that the node centrality is a major determinant of the diffusion of information and behaviour from the nodes [30, 31]. In 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 the diffusion of behaviour because of reinforcement from clustered neighbours [29]. We obtain results different from those of previous works 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 the loops in the short run.

All of the above findings suggest that the propagation of economic shocks among firms through supply chains is quite different from the diffusion of information and behaviour among individuals, most likely because upstreamness is important in supply chains, unlike in other networks.

Finally, our experiments reveal that substitution between only neighbouring nodes indirectly linked a few steps apart in the network can mitigate the propagation of the negative effect as much as can substitution between distant nodes. Although the importance of supplier substitution for sustainable supply chains has been empirically found in several previous studies [17, 18, 4, 28], such studies do not compare different types of substitution for higher sustainability. Furthermore, although some studies in network science examine how the rewiring of nodes improves sustainability in the context of airline and power grid networks [35, 37], 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 the 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 the possible substitution of neighbouring suppliers in supply chains for affected suppliers in the event of supply chain disruption.

Method

Data

This study uses two datasets. The first set comes from the Company Information Database and Company Linkage Database of Tokyo Shoko Research (TSR) for 2020, which contains attributes for most firms in Japan, including small and medium-sized enterprises (SMEs), and their major domestic clients and suppliers. After removing those 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 the sales of each firm to final consumers and the transaction volume of each supply chain link, we estimate these factors using the IO table of Japan in 2015 [41] so that the aggregate transactions between industries and final consumers according to firm-level estimations match those in the IO table.

The other dataset 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 (METI). The BSJ targets firms in Japan with 50 or more employees and initial capital of 30 or more million yen, i.e., relatively large firms. The response rate of the BSJ in 2019 is 78.8%, and the number of respondent firms is 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 study, 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.

Model

We extend dynamic agent-based models that focus on domestic supply chains by incorporating imports of inputs and exports of outputs [16, 17, 18, 42]. This subsection and Fig. 7 provide an overview of the model, with further details provided in the SI file.

The model assumes that firms in a country are linked not only with each other through domestic supply chains but also with foreign input and output markets through international trade, as illustrated by the arrows in Fig. 7. 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 [38] and categorised into 1,460 classifications. Because our data include

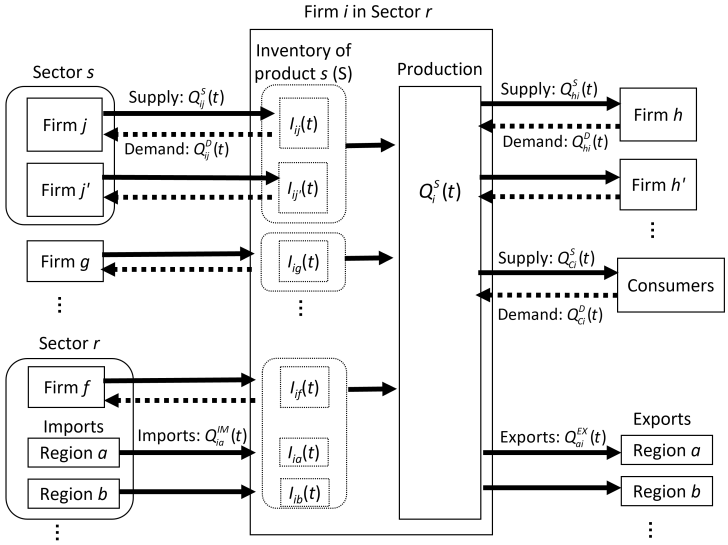

Figure 7: **Overview of the agent-based model.** Products flow from left to right, whereas orders flow in the opposite direction.

values of imported inputs from each broadly defined foreign region but not the product type of such 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 predetermined 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 are shown to be able to find other suppliers to identify product 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 are from suppliers in the same sector, for example, firms j and j' in Fig. 7, 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 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. On day 1, an economic shock, such as a new policy or natural disaster, disrupts imports from particular foreign regions (Q^{IM}_{ia}). After the shock, firms directly facing disrupted supply chains (firms h and h') reduce their production level because of the supply shortages of inputs. Conversely, the disruption of exports to certain regions (Q^{EX}_{ai}) 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 the production level, 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.

Simulations

Using an agent-based model and firm-level data with supply chain information, we simulate how the disruption of imports or exports due to a new 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) the industries whose imports or exports are disrupted (all or one of the manufacturing industries). For example, in one scenario, we assume a reduction in the global imports of all intermediate products by 60% for four weeks and simulate the total production of Japan day by day. In addition, 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 due to 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 of each of the other industries. By doing so, we can examine spillovers of the effect of industry-specific disruption across industries.

HHD

HHD decomposes a flow in a network into a potential flow component and a loop flow component. A potential flow from one node to another is determined by the upstreamness/downstreamness of the nodes in a network [33], 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 the network is complex [34, 43, 44, 45].

Specifically, HHD is explained by the following equations. Suppose that a network is denoted by a set of flows from node i to j, represented by X_{ij}. For simplicity, we assume that $\forall i, j\ X_{ij} \geq 0$. A_{ij} is a binary adjacency matrix generated from X_{ij}: A_{ij} equals 1 if $X_{ij} > 0$ and 0 otherwise. We define a "net flow" F_{ij} by $F_{ij} = X_{ij} - X_{ji}$, and a "net weight" w_{ij} by $w_{ij} = A_{ij} + A_{ji}$. Note that w_{ij} is symmetric, $w_{ij} = w_{ji}$, and nonnegative, $w_{ij} \geq 0$, for any pair of i and j. Then, the HHD value is given by

$$F_{ij} = F_{ij}^{(c)} + F_{ij}^{(p)}, \tag{1}$$

where loop flow $F_{ij}^{(c)}$ satisfies

$$\sum_j F_{ij}^{(c)} = 0, \tag{2}$$

meaning that the loop flows are divergence free. Potential flow $F_{ij}^{(p)}$ can be expressed as

$$F_{ij}^{(p)} = w_{ij}(\phi_i - \phi_j), \tag{3}$$

where ϕ_i is the potential of node i that identifies its upstreamness in the network. Equation (3) indicates that potential flow $F_{ij}^{(p)}$ is the difference in the potential between two nodes when they are linked and zero when they are not linked. We further assume that

$$\sum_i \phi_i = 0 \tag{4}$$

for normalisation purposes. Then, Equations (1)–(4) can be uniquely solved for $F_{ij}^{(c)}$, $F_{ij}^{(p)}$, and ϕ_i for all i and j in the whole network.

SI Fig. 5 shows the average potential of importers from various regions by industry, indicating that manufacturing industries (codes 9-32) are relatively upstream, while wholesale (50-55), retail (56-61), and finance (62-67) industries are more downstream, confirming the finding in the literature [34].

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 production loss, as the two are related to the number of nodes affected initially and subsequently. To measure the 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, then 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 HHD [33]. Using HHD, we can decompose a flow from one 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 [32, 34]. Our firm-level measure of upstreamness can capture heterogeneity in upstreamness across firms within the same industry, unlike the industry-level measures of upstreamness often used in the literature [46, 47, 48, 49, 50]. 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. Supply chains consist of a number of loops in a complex way [17, 32] 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, then the production loss can be smaller than it would be otherwise. Therefore, we hypothesise that the number of loops that pass through importers is negatively correlated with production loss. Using 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, which 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.

We test these hypotheses with ordinary least squares (OLS) estimations of the following equation:

$$\ln \mathit{ProdLoss}_{sc} = \alpha + \beta \ln \mathit{DisruptImp}_{sc} + X_{sc}\delta' + \epsilon_{sc}, \tag{5}$$

where $\mathit{ProdLoss}_{sc}$ indicates the predicted total loss in value-added production in Japan due to the disruption of imports from country c to industry s by 80% for 28, 42, or 60 days and $\mathit{DisruptImp}_{sc}$ is the value of disrupted imports. X_{sc} indicates a vector of variables that represent the network topology of importers in industry s from country c, namely, the number of importers and their average outdegree, indegree, betweenness centrality, potential, loop flows, and local clustering coefficient. We run separate regressions using data at the exporter country-industry level from simulations assuming different durations of import disruption to examine how the effect of network topology differs depending on the duration. In the benchmark specification, we include all the variables for network topology in each regression and illustrate the results in Fig. 5. In addition, we experiment with those specifications where only one of the topology variables is used as X_{sc} in Equation (5) and show the results in SI Tables 4-6, confirming the robustness of the benchmark results.

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Firm-level Propagation of the Effect of the Disruption of International Trade through Domestic Supply Chains

Supplementary Information

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Method

Data

The Tokyo Shoko Research (TSR) data do not contain the sales of each firm to final consumers or the transaction volume of each supply chain link. We estimate the former by dividing the final consumption of each industrial sector, taken from the input–output (IO) table of Japan in 2015 [1], among all firms in the sector in proportion to their sales. In addition, we estimate the transaction volume of each link using the following algorithm. First, each supplier's total sales less sales to final consumers are tentatively divided among its clients in proportion to the clients' sales. Second, the tentative volume of each supplier-client transaction is summed up within each pair of industries. Then, we adjust the interfirm transaction volume so that the sum of the estimated volume within any industry pair is equal to the actual volume taken from the IO table of Japan in 2015.

We combine the TSR data with trade information at the firm level taken from the Basic Survey of Japanese Business Structure and Activities (BSJ) data, using firm identification numbers for the BSJ that are also included in the TSR data. Because the number of firms in the BSJ data is substantially smaller than that in the TSR data, we have to ignore the imports and exports of small firms that are not included in the BSJ data. However, the total imports and exports of firms in the BSJ data are 47.7 and 83.0 trillion yen, respectively, whereas the total imports and exports of Japan in 2019 taken from the customs data are 78.6 and 76.9 trillion yen [2], respectively[1]. Therefore, we assume that the BSJ data cover most exports of Japanese firms. Most exporters may be included in the BSJ data because only productive and thus large firms can usually export [3, 4]. The total exports in the BSJ data exceed those in the customs data, possibly because the indirect exports of firms through traders are double counted as exports of both producers and traders in the BSJ data. In contrast, the imports in our data are undervalued because those of small and medium-sized enterprises (SMEs) are not included. In particular, imports from China in our data, 8.55 trillion yen, are particularly undervalued compared with those in the BSJ data, 18.5 trillion yen. The reason for this is possibly that a number of SMEs that import inputs rely on imports from China. In contrast, those imports from Asia except for China in our data are 13.5 trillion yen and relatively closer to those in the BSJ data, 18.9 trillion.

Model

Supply and demand

In the following, we denote the daily supply of the intermediate product of supplier i to client h on day t by $Q^{\mathrm{S}}_{hi}(t)$, the supply to final consumers by $Q^{\mathrm{S}}_{Ci}(t)$, and the exports to region a by $Q^{\mathrm{EX}}_{ai}(t)$. Then, the

[1] We also use BSJ data for 2018 to check the overall trend in the data and the validity of the use of the data for 2019.

production of firm i on day 0 is given by

$$Q_i^{\mathrm{S}}(0) = \Sigma_h Q_{hi}^{\mathrm{S}}(0) + Q_{Ci}^{\mathrm{S}}(0) + \Sigma_a Q_{ai}^{\mathrm{EX}}(0). \tag{1}$$

We assume that each firm predicts that the demand for its product on day t is equal to that on the previous day, $Q_i^{\mathrm{D}}(t-1)$. To meet this demand, firm i needs supplier j's product in an amount, $Q_{ij}^{\mathrm{S}}(0)Q_i^{\mathrm{D}}(t-1)/Q_i^{\mathrm{S}}(0)$, because $Q_{ij}^{\mathrm{S}}(0)$ represents the supply of supplier j's product to firm i in the initial state, and $Q_i^{\mathrm{D}}(t-1)/Q_i^{\mathrm{S}}(0)$ is the ratio of the current demand to initial supply.

In addition, firms demand intermediates to hold their inventories in case of supply chain disruption. Specifically, firm i has an inventory of the intermediate produced by firm j on day t, $I_{ij}(t)$, and intends to restore this inventory to a level equal to a given number of days, n_i, of the utilisation of supplier j's product, $n_i Q_{ij}^{S}(0)$. We assume that n_i is randomly determined by a Poisson distribution, where the mean is n in the beginning of the simulation. Note that there are data indicating the inventory of each firm's own products but not that of the intermediate goods used by each firm. Therefore, we rely on this probabilistic assignment. Following Inoue and Todo [5], n is set to 9 such that the model replicates the economic reaction to the Great East Japan earthquake. In addition, to avoid a bullwhip effect, i.e., large fluctuations across simulations, n_i is assumed to be greater than or equal to 4. When actual inventory $I_{ij}(t)$ is smaller than its target $n_i Q_{ij}^{\mathrm{S}}(0)$, firm i increases its inventory gradually by $1/\tau$ of the gap in one day such that it reaches the target in τ days. We assume that $\tau = 6$, following an existing study [6].

Combined with the abovementioned two purposes, i.e., production and inventory, firm i's demand for the product of its supplier j on day t, denoted by $Q_{ij}^{\mathrm{D}}(t)$, is given by

$$Q_{ij}^{\mathrm{D}}(t) = Q_{ij}^{\mathrm{S}}(0)\frac{Q_i^{\mathrm{D}}(t-1)}{Q_i^{\mathrm{S}}(0)} + \frac{1}{\tau}\left[n_i Q_{ij}^{\mathrm{S}}(0) - I_{ij}(t)\right]. \tag{2}$$

Inventory should not be considered for a service supplier. This aspect is realised by the second term and is thus omitted, and $Q_{ij}^{\mathrm{D}}(t)$ is always equal to $Q_{ij}^{\mathrm{S}}(0)$, where j belongs to a service sector.

Accordingly, total demand for the product of supplier i on day t, $Q_i^{\mathrm{D}}(t)$, is given by the sum of total demand from its client firms and final consumers and exports:

$$Q_i^{\mathrm{D}}(t) = \Sigma_h Q_{hi}^{\mathrm{D}}(t) + Q_{Ci}^{\mathrm{D}} + \Sigma_a Q_{ai}^{\mathrm{EX}}(0). \tag{3}$$

On day 0, we assume that the level of inventory is equal to its target level ($n_i Q_{ij}^{\mathrm{S}}(0) = I_{ij}(0)$) and that the demand for the product of firm i on the previous day is equal to its production ($Q_i^{\mathrm{D}}(t-1) = Q_i^{S}(0)$). Therefore, there is no excess supply or demand on day 0: $Q_{ij}^{\mathrm{S}}(0) = Q_{ij}^{\mathrm{D}}(0)$ and $Q_i^{\mathrm{S}}(0) = Q_i^{\mathrm{D}}(0)$.

Disruption of supply chains

Now, let us suppose that the imports of intermediate goods from some foreign countries or regions are disrupted because of a new trade policy or natural disaster. When facing a shortage of imports of an intermediate product from region a, firm i can use its inventory of the intermediate, including the inventory of the same intermediate from other domestic suppliers in the same sector and imports from other regions. Therefore, the maximum possible production of firm i, limited by the product inventory of the sector s intermediate on day t, $\bar{Q}_{i(s)}^{\mathrm{S}}(t)$, is given by

$$\bar{Q}_{i(s)}^{\mathrm{S}}(t) = \frac{\Sigma_{j\in s} I_{ij}(t)}{\Sigma_{j\in s} Q_{ij}^{\mathrm{S}}(0)} Q_i^{\mathrm{S}}(0), \tag{4}$$

where $\Sigma_{j\in s}I_{ij}(t)$ is firm i's total inventory of the intermediate of sector s, including imports, on day t and $\Sigma_{j\in s}Q^{\mathrm{S}}_{ij}(0)$ is the amount of intermediate s required to produce the initial production level of firm i. Because we assume a Leontief production function, the maximum possible production of firm i on day t is constrained by the availability of inputs and given by the following:

$$Q^{\mathrm{S}}_{\mathrm{max}i}(t) = \mathrm{Min}_s(\bar{Q}^{\mathrm{S}}_{i(s)}(t)). \tag{5}$$

Therefore, the supply of firm i on day t is determined either by the maximum production capacity when it is smaller than the demand or by the demand and thus given by

$$Q^{\mathrm{S}}_i(t) = \mathrm{Min}\left(Q^{\mathrm{S}}_{\mathrm{max}i}(t), Q^{\mathrm{D}}_i(t)\right). \tag{6}$$

In alternative scenarios, we assume that the exports of products to some foreign countries or regions are stopped because of a trade policy or natural disaster. In this case, the demand for firms exporting to foreign regions declines by the amount of exports. The supply of firm i is still determined by Equation (6).

In either scenario, the supply and demand of firms that are not directly engaged in international trade may be affected by supply chain disruption because of propagation of its effect throughout supply chains.

Rationing of production

When the total demand for firm i's product is greater than its production capacity, the firm cannot satisfy the demand of its clients and consumers and thus has to ration its production to them. Suppose that firm i has clients $h \in \{1, ..., H\}$, final consumers, and importers. The supply to each client, consumer, and importer is determined by the following steps, where the demand of agents, which is relatively small compared with their initial demand, is prioritised [5]. To explain the associated procedure, let us define the amount of production that has not been rationed and remains to be rationed at the beginning of step x as $Q^{\mathrm{R}}_i[x]$. We also denote the minimum ratio of current demand to initial demand by $q^{\mathrm{D}}_{\mathrm{min}}(t) \equiv \mathrm{Min}(q^{\mathrm{D}}_{hi}(t), q^{\mathrm{D}}_{CEXi}(t))$. Here, $q^{\mathrm{D}}_{hi}(t) \equiv Q^{\mathrm{D}}_{hi}(t)/Q^{\mathrm{S}}_{hi}(0)$ is the ratio of the demand of client h for the product of firm i to its initial demand, and $q^{\mathrm{D}}_{CEXi}(t) \equiv (Q^{\mathrm{D}}_{Ci}(t) + \Sigma_a Q^{\mathrm{EX}}_{ai}(t))/(Q^{\mathrm{S}}_{Ci}(0) + \Sigma_a Q^{\mathrm{EX}}_{ai}(0))$ is the corresponding ratio for the sum of the demand of final consumers and importers.

In the first step, $x = 1$ and $Q^{\mathrm{R}}_i[1] = Q^{\mathrm{S}}_i(t)$ by definition. At every step, the following equation is evaluated:

$$Q^{\mathrm{R}}_i[x] \geq q^{\mathrm{D}}_{\mathrm{min}}(t)Q^{\mathrm{D}}_i(t). \tag{7}$$

If Equation (7) holds, then firm i rations to each client firm, consumer, and importer the amount of its demand multiplied by the minimum demand ratio $q^{\mathrm{D}}_{\mathrm{min}}(t)$. The remainder of the production, $Q^{\mathrm{R}}_i[x+1] = Q^{\mathrm{R}}[x] - q^{\mathrm{D}}_{\mathrm{min}}(t)Q^{\mathrm{D}}_i(t)$, flows to the next step. In addition, the demand from each client firm, consumer, and importer is removed by the ratio q^{D}. Therefore, a client firm or the aggregate consumers and importers that satisfy its demand (or whose rate of current demand to initial demand is the minimum) is dropped. On the other hand, if Equation (7) does not hold at some step x, then firm i rations to each client, consumer, and importer the amount of its demand multiplied by the ratio of the remaining production to demand defined by $q^{\mathrm{D}}_{\mathrm{r\text{-}d}_i} \equiv Q^{\mathrm{R}}_i[x]/Q^{\mathrm{D}}_i(t)$. At this step, the procedure ends because $Q^{\mathrm{R}}_i[x+1]$ becomes zero.

Under this rationing policy, the inventory of firm j's product held by firm i on day $t+1$ is updated to

$$I_{ij}(t+1) = I_{ij}(t) + Q^{\mathrm{S}}_{ij}(t) - Q^{\mathrm{S}}_{ij}(0)\frac{Q^{\mathrm{S}}_i(t-1)}{Q^{\mathrm{S}}_i(0)}. \tag{8}$$

This equation, combined with Equations (2) and (6), determines the demand of firm i for the intermediate good supplied by firm j on day $t+1$, $Q^{\mathrm{D}}_{ij}(t+1)$, and the total demand for firm i's product, $Q^{\mathrm{D}}_{i}(t+1)$. The supply of firm i on day $t+1$, $Q^{\mathrm{S}}_{i}(t+1)$, is then determined by Equation (6).

Limitations

Several caveats of this study should be noted. First, our benchmark model allows for changes in supply chain links after import or export disruption with the predisruption partners but not with new partners. Second, our analysis is based on an agent-based model without any price. Because of these two shortcomings, our conclusions should be viewed with caution and applied only to short-term analysis. Therefore, the long-term scenarios where we assume import or export disruption for two months may lead to an overvaluation of the effect of supply chain disruption due to the rigidity of supply chains. Finally, our trade data are based on BSJ data in which only large firms are included, and thus, imports are particularly undervalued (see the Data section). Because SMEs that import inputs often rely only on China, those imports from China in our data (Data section) and their effect on production in our simulation may be underestimated.

Results

Disruption of exports

Fig. 2 illustrates the simulation results for the disruption of global exports, while Fig. 3 shows the results by region. We find three notable differences between the effects of import and export disruption. First, the disruption of the imports of intermediate goods has a far greater impact on the total production of the economy than do disruptions of the exports of final products. For example, reductions in global imports and exports by 80% for 2 months reduce value-added production by 41 and 2.7 trillion yen, respectively (Fig. 2). Despite the larger effect of import disruption than of export disruption, the total annual imports in the data used in our simulation, 45 billion yen, are approximately half of the total annual exports, 81 billion yen. Moreover, the share of imports in the total value of intermediates, 2.8%, is substantially smaller than the share of exports in total production, 16.7%. Second, as the duration of export disruption is extended, the loss in value-added production naturally increases. However, the ratio of the loss in value added to total value-added production declines, although the loss ratio increases exponentially in the case of import disruption. For example, Panel (b) of Fig. 2 indicates that when global exports are disrupted by 80% for two weeks, the total production of Japan declines by 4.4% during that period. When the duration becomes four weeks and two months, the rate of the loss in value-added production declines to 3.7 and 3.2%, respectively. Finally, the loss ratio is closely proportional to the strength of disruption, i.e., the rate of reduction in exports. For example, when exports to the world are disrupted by 20, 40, 60, and 80% for two months, total production declines by 0.65, 1.3, 2.1, and 3.2%, respectively (inset of Panel (b) in Fig. 2).

Differences between import and export disruption

The differences between import and export disruption are due to the following three reasons. First, the effect of import disruption, i.e., reduction in supplies of inputs, can be partially absorbed by utilising the inventory of disrupted inputs. Therefore, the effect of import disruption is initially quite small. In contrast, the effect of export disruption, i.e., reduction in demand, cannot be absorbed but rather is aggravated by inventory usage. When exporting firms face the shrinkage of their exports, their demand for intermediate products also declines. Because exporters hold inventories of their intermediates, they use these inventories for decreased production and drastically reduce their number of purchases from their suppliers immediately after export disruption. As a result, the production of their suppliers declines substantially, leading to a large initial reduction in value-added production relative to total production.

Second, although the initial effect of import disruption is alleviated by the use of input inventory, its effect is aggravated over time as inventory becomes exhausted. Moreover, the effect propagates downstream through supply chains because a decrease in the production of a firm results in a decline in the production of its clients. The propagation is gradual because of the input inventory held by the clients but can be substantial after a time. In contrast, how the effect of export disruption is influenced by inventory is the opposite. Once the excess inventories of intermediates are used shortly after export disruption, exporters purchase more intermediates from their suppliers, and thus, the rate of production loss declines in the long run compared to that immediately after the disruption.

Finally, the effect of import disruption is "leveraged" or propagated to more firms as the shock proceeds downstream to clients through input shortages. However, there is no such leverage effect of export disruption because firms facing a reduction in demand directly or indirectly because of export disruption simply reduce their production by reducing demand. As a result, the rate of value-added loss due to import disruption increases exponentially as the strength of disruption rises, while that due to export disruption is proportional to its strength.

We experiment with simultaneous import and export shocks (SI Fig. 1) to determine the outcome if the shocks occur at the same time. Although the total reductions are not simple summations of those obtained from import and export shocks independently, they are slightly smaller than the summations. As the effect of import disruption is far greater than the effect of export disruption, we focus on import disruption in the following analyses.

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Figures and Tables

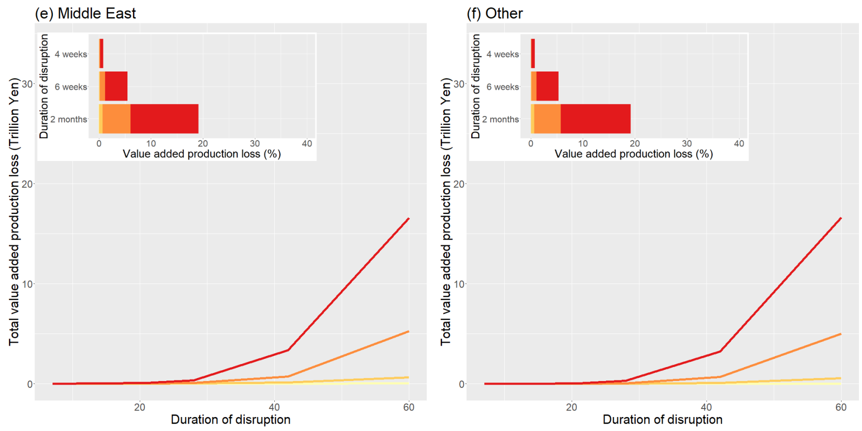

Figure 1: **The effect of the disruption of imports from various areas on domestic production.** The main panels in the figure show the total loss in value-added production in Japan when imports from each region are disrupted to a particular extent (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panels show the ratio of the loss in value-added production to total production when imports from each region are disrupted at a particular strength for 4 and 6 weeks and 2 months. The right edge of each colour of the bars indicates the loss rate at the corresponding strength (20, 40, 60, or 80%). The titles of the panels are (e) and (f) because they are supplements of Fig. 2 in the main text.

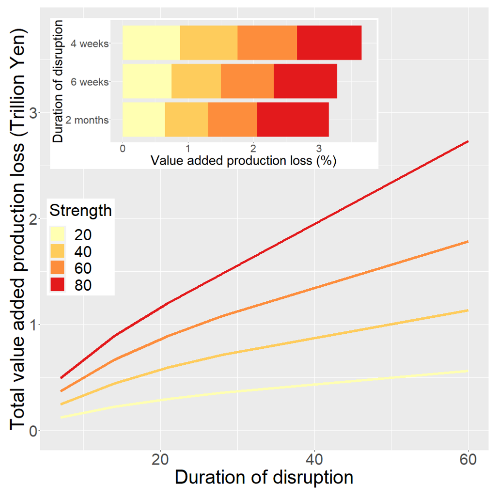

Figure 2: **The effect of the disruption of global exports on domestic production.** The main panels in the figure show the total loss of value-added production in Japan when exports to the world are disrupted to a particular strength (20-80%) for a particular duration (from 2 weeks to 2 months). The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

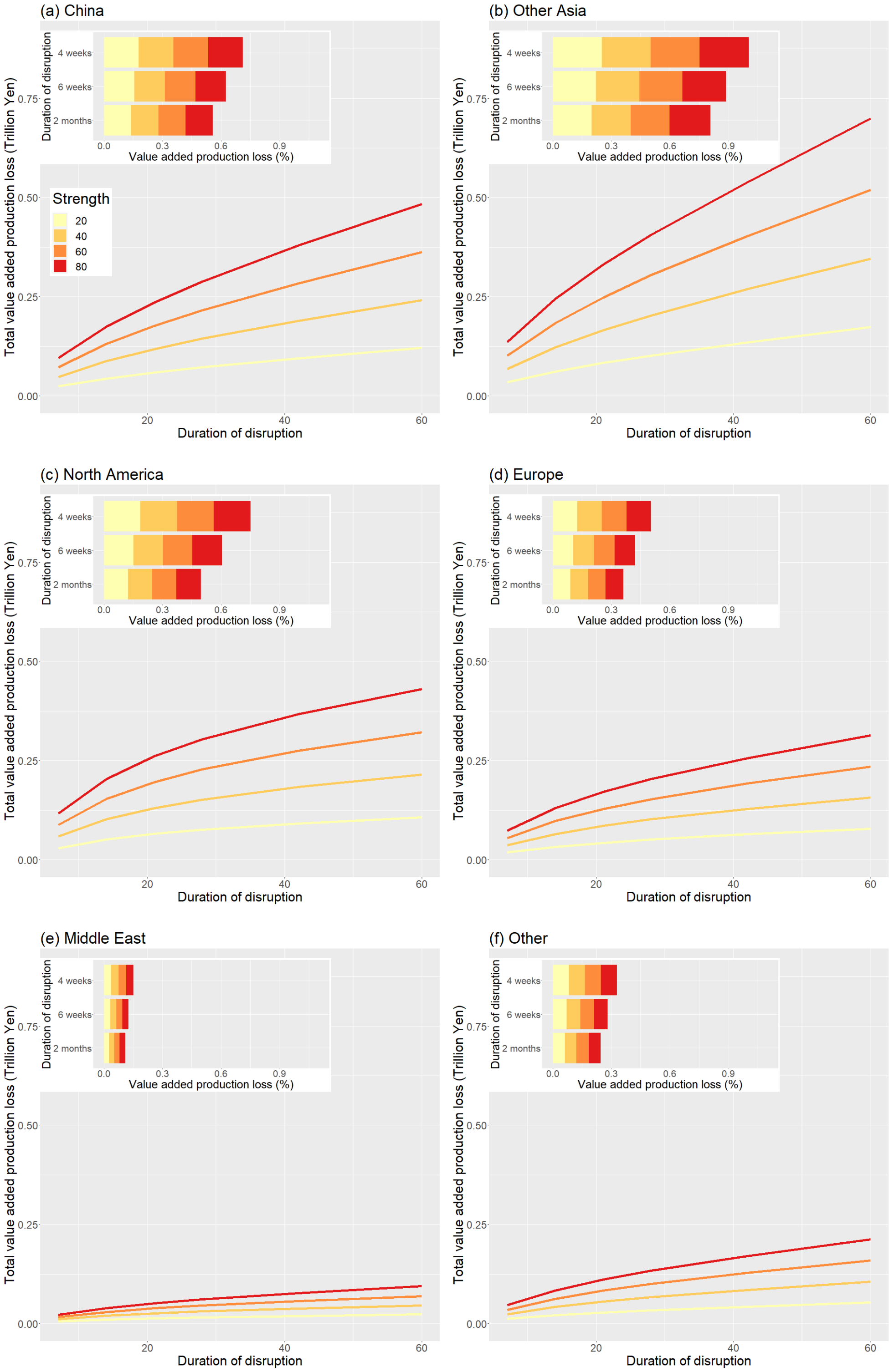

Figure 3: **The effect of the disruption of exports to various areas on domestic production.** The main panels in the figure show the total reductions in production in Japan when exports to given areas are disrupted to a particular extent (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panels show the ratio of the loss in value-added production to total production when exports to each region are disrupted at a particular strength for 4 and 6 weeks and 2 months. The right edge of each colour of the bars indicates the loss rate at the corresponding strength (20, 40, 60, or 80%). “Other Asia” represents Asian countries except for China.

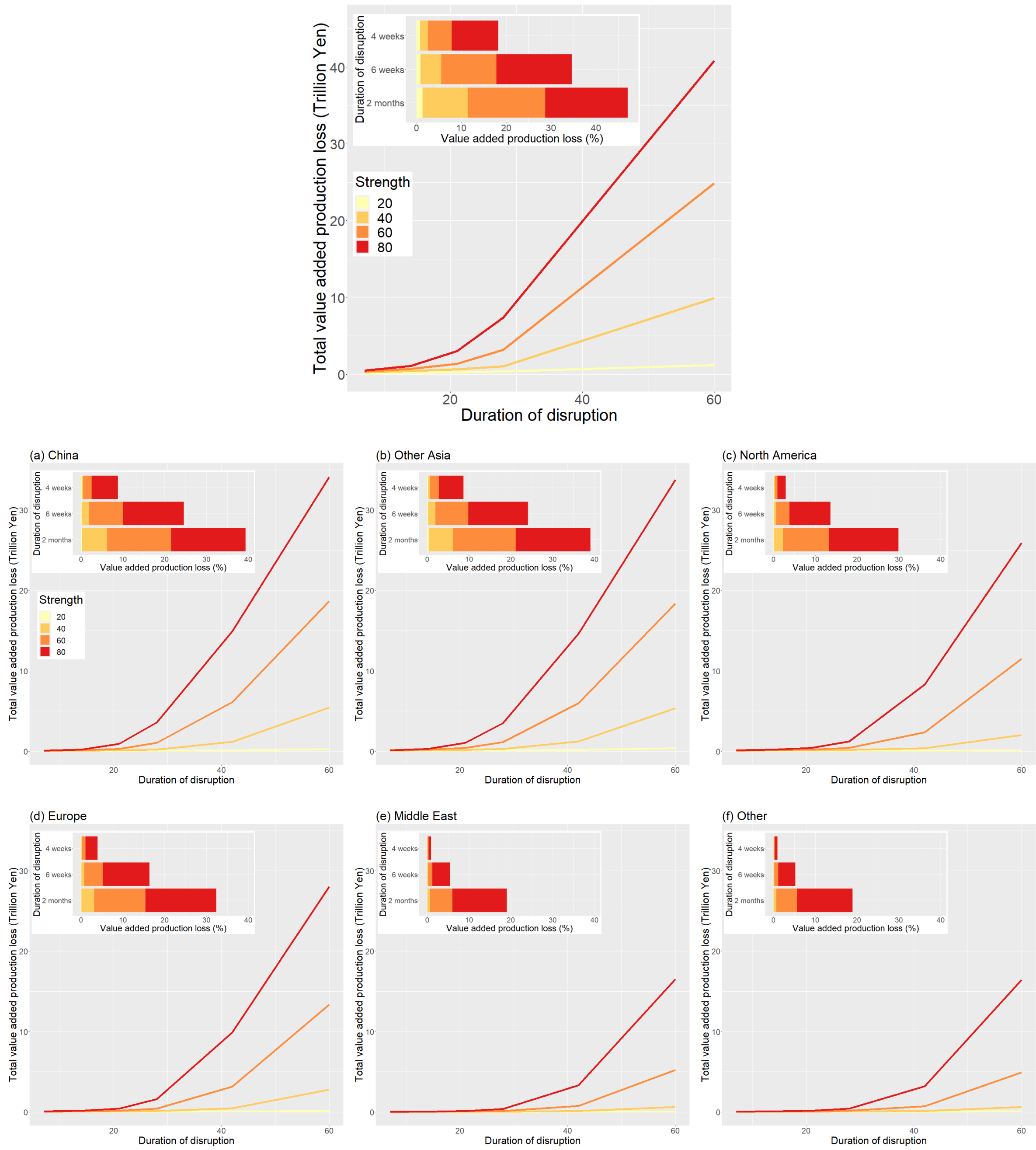

Figure 4: **The effect of the simultaneous disruption of imports and exports on domestic production.** The main panels in the figure show the total reductions in production in Japan when global and specific areas' imports and exports are simultaneously disrupted to a particular extent (20-80%) for a particular duration (from 2 weeks to 2 months). The inset panel shows the ratios of the losses in value-added production in Japan to total production when disruptions occur at a particular strength for a particular duration (4 and 6 weeks, and 2 months). Note that the bars are not cumulative, but the right edges of the bars indicate the rates of loss at the corresponding strengths. "Other Asia" represents Asian countries except for China.

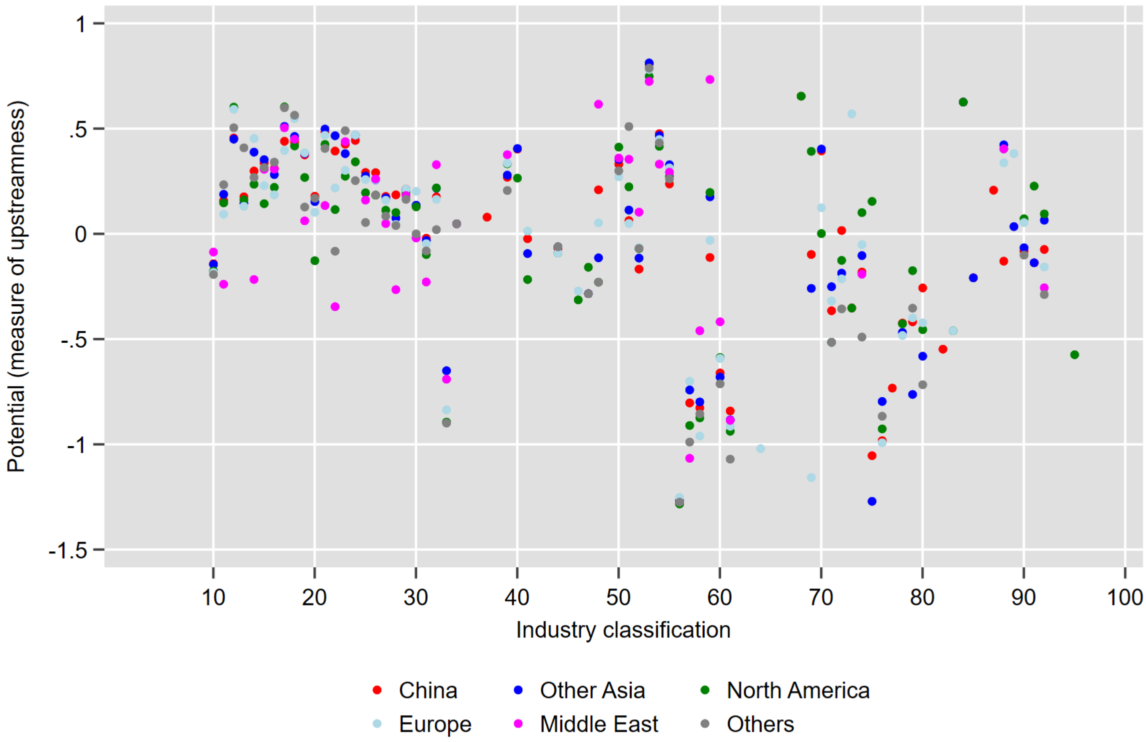

Figure 5: **Average potential of importing firms by industry and region.** The horizontal axis indicates the Japan Standard Industrial Classification (JSIC) two-digit industries of importers, whereas the vertical axis indicates the mean of the potential of importing firms. The colour of each dot represents the exporting country.

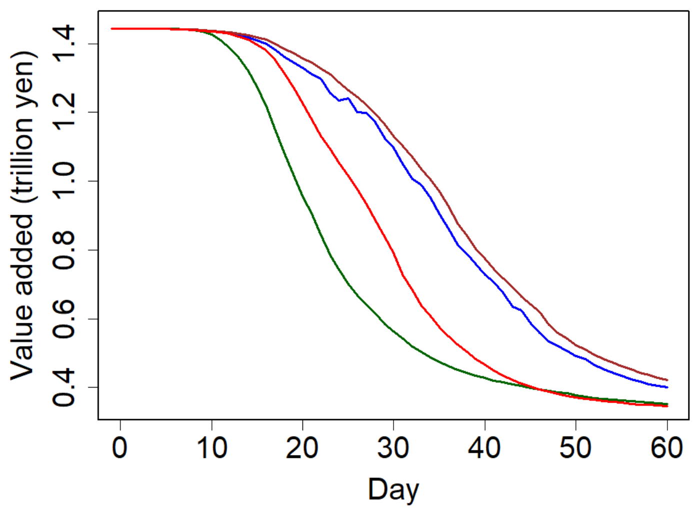

Figure 6: **Production decrease due to import disruption using different assumptions on the substitution of suppliers: The China scenario.** This figure illustrates the total changes in daily value added after the disruption of imports from China by 80% for 60 days. The green, red, brown, and blue lines 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.

Table 1: JSIC (Rev. 13, 2013) [7]: 1-digit level.

1-digit code	Industry
A	AGRICULTURE AND FORESTRY
B	FISHERIES
C	MINING AND QUARRYING OF STONE AND GRAVEL
D	CONSTRUCTION
E	MANUFACTURING
F	ELECTRICITY, GAS, HEAT SUPPLY AND WATER
G	INFORMATION AND COMMUNICATIONS
H	TRANSPORT AND POSTAL ACTIVITIES
I	WHOLESALE AND RETAIL TRADE
J	FINANCE AND INSURANCE
K	REAL ESTATE AND GOODS RENTAL AND LEASING
L	SCIENTIFIC RESEARCH, PROFESSIONAL AND TECHNICAL SERVICES
M	ACCOMMODATIONS, EATING AND DRINKING SERVICES
N	LIVING-RELATED AND PERSONAL SERVICES AND AMUSEMENT SERVICES
O	EDUCATION, LEARNING SUPPORT
P	MEDICAL, HEALTH CARE AND WELFARE
Q	COMPOUND SERVICES
R	SERVICES, N.E.C.
S	GOVERNMENT, EXCEPT ELSEWHERE CLASSIFIED
T	INDUSTRIES UNABLE TO CLASSIFY

Table 2: JSIC (Rev. 13, 2013) [7]: 2-digit level.

2-digit code for manufacturing industries	Industry
9	MANUFACTURE OF FOOD
10	MANUFACTURE OF BEVERAGES,TOBACCO AND FEED
11	MANUFACTURE OF TEXTILE PRODUCTS
12	MANUFACTURE OF LUMBER AND WOOD PRODUCTS, EXCEPT FURNITURE
13	MANUFACTURE OF FURNITURE AND FIXTURES
14	MANUFACTURE OF PULP, PAPER AND PAPER PRODUCTS
15	PRINTING AND ALLIED INDUSTRIES
16	MANUFACTURE OF CHEMICAL AND ALLIED PRODUCTS
17	MANUFACTURE OF PETROLEUM AND COAL PRODUCTS
18	MANUFACTURE OF PLASTIC PRODUCTS, EXCEPT OTHERWISE CLASSIFIED
19	MANUFACTURE OF RUBBER PRODUCTS
20	MANUFACTURE OF LEATHER TANNING, LEATHER PRODUCTS AND FUR SKINS
21	MANUFACTURE OF CERAMIC, STONE AND CLAY PRODUCTS
22	MANUFACTURE OF IRON AND STEEL
23	MANUFACTURE OF NON-FERROUS METALS AND PRODUCTS
24	MANUFACTURE OF FABRICATED METAL PRODUCTS
25	MANUFACTURE OF GENERAL-PURPOSE MACHINERY
26	MANUFACTURE OF PRODUCTION MACHINERY
27	MANUFACTURE OF BUSINESS ORIENTED MACHINERY
28	ELECTRONIC PARTS, DEVICES AND ELECTRONIC CIRCUITS
29	MANUFACTURE OF ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES
30	MANUFACTURE OF INFORMATION AND COMMUNICATION ELECTRONICS EQUIPMENT
31	MANUFACTURE OF TRANSPORTATION EQUIPMENT
32	MISCELLANEOUS MANUFACTURING INDUSTRIES

Table 3: Overview of Japanese firms' imports to and exports from foreign areas.

Area	Import Volume (trillion yen)	# of links	Export Volume (trillion yen)	# of links
Global	47.7	14,476	83.0	19,572
Asia	24.3	8,540	41.5	10,172
China	8.7	4,197	17.1	4,635
Other Asia	15.7	4,343	24.3	5,537
North America	4.6	2,257	19.0	3,339
Europe	5.2	2,575	12.4	2,951
Middle East	9.8	280	2.9	1,032
Other	3.8	824	7.2	2,078

Table 4: Regression results assuming import disruption for 28 days.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
ln_directshock	0.513***	0.962***	1.003***	1.002***	1.003***	1.029***	1.007***	0.666***	0.581***	0.618***	0.694***
	(0.109)	(0.105)	(0.119)	(0.120)	(0.120)	(0.117)	(0.119)	(0.119)	(0.107)	(0.109)	(0.138)
ln_importer	1.265***							0.818***			
	(0.228)							(0.282)			
ln_outdegreemean		1.435***						1.479**			
		(0.508)						(0.565)			
ln_indegreemean			0.932*					-0.487			
			(0.481)					(0.563)			
betweennessmean				4,998				11,757			
				(4,644)				(7,161)			
potentialmean					0.0809			1.877*			
					(1.360)			(1.028)			
ln_loopflowsummean						-1.400***		-0.869**			
						(0.320)		(0.405)			
clusteringmean							-4.253	-0.304			
							(7.443)	(6.316)			
ln_outdegreesum									1.004***		
									(0.212)		
ln_indegreesum										0.983***	
										(0.224)	
ln_betweennesssum											0.564***
											(0.176)
Constant	-10.65***	-9.704***	-9.157***	-8.147***	-8.144***	-1.681	-7.894***	-7.388**	-10.96***	-10.91***	-1.415
	(0.928)	(0.954)	(1.003)	(0.693)	(0.705)	(1.656)	(0.870)	(2.935)	(1.009)	(1.085)	(2.035)
Observations	110	110	110	110	110	110	110	110	110	110	110
R-squared	0.589	0.520	0.481	0.465	0.464	0.548	0.467	0.648	0.598	0.575	0.528

Robust standard errors are in parentheses.
*** p<0.01, ** p<0.05, and * p<0.1.

Table 5: Regression results assuming import disruption for 42 days. The results in Column (8) of this table are used in Fig. 10.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
ln_directshock	0.394***	0.865***	0.891***	0.901***	0.908***	0.938***	0.907***	0.569***	0.472***	0.455***	0.591***
	(0.124)	(0.126)	(0.127)	(0.136)	(0.135)	(0.133)	(0.135)	(0.137)	(0.123)	(0.115)	(0.147)
ln_importer	1.311***							0.856***			
	(0.241)							(0.306)			
ln_outdegreemean		1.339**						1.072			
		(0.542)						(0.711)			
ln_indegreemean			1.543**					0.534			
			(0.653)					(0.865)			
betweennessmean				3,850				11,582			
				(4,751)				(7,704)			
potentialmean					1.900			3.399***			
					(1.557)			(1.173)			
ln_loopflowsummean						-1.401***		-0.801*			
						(0.368)		(0.453)			
clusteringmean							-5.559	-0.590			
							(7.095)	(6.725)			
ln_outdegreesum									1.022***		
									(0.226)		
ln_indegreesum										1.117***	
										(0.253)	
ln_betweennesssum											0.566***
											(0.179)
Constant	-7.455***	-6.330***	-6.501***	-4.869***	-5.345***	1.554	-4.548***	-5.555*	-7.724***	-7.953***	1.882
	(1.041)	(1.085)	(1.238)	(0.794)	(0.848)	(1.871)	(0.964)	(3.342)	(1.142)	(1.237)	(2.061)
Observations	112	112	112	112	112	112	112	112	112	112	112
R-squared	0.485	0.405	0.405	0.360	0.374	0.441	0.363	0.568	0.490	0.498	0.420

Robust standard errors are in parentheses.
*** p<0.01, ** p<0.05, and * p<0.1.

Table 6: Regression results assuming import disruption for 60 days.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
ln_directshock	0.291**	0.656***	0.678***	0.687***	0.695***	0.712***	0.692***	0.391**	0.338***	0.311***	0.442***
	(0.125)	(0.133)	(0.132)	(0.141)	(0.139)	(0.141)	(0.140)	(0.158)	(0.125)	(0.114)	(0.156)
Number of importers (log)	1.026***							0.738**			
	(0.238)							(0.300)			
Average outdegree (log)		1.168**						0.894			
		(0.556)						(0.577)			
Average indegree (log)			1.552**					0.820			
			(0.704)					(0.611)			
Average betweenness				4,193				10,049			
				(5,092)				(11,787)			
Average potential					2.077			3.335***			
					(1.552)			(1.174)			
Average loop flows (log)						-0.920**		-0.371			
						(0.372)		(0.384)			
Average clustering coefficient							-3.794	1.465			
							(6.424)	(6.438)			
ln_outdegreesum									0.833***		
									(0.237)		
ln_indegreesum										0.944***	
										(0.266)	
ln_betweennesssum											0.449**
											(0.173)
Constant	-3.722***	-2.974**	-3.343**	-1.703**	-2.223**	2.521	-1.476	-4.317*	-4.025***	-4.305***	3.659*
	(1.096)	(1.175)	(1.344)	(0.833)	(0.894)	(1.933)	(0.965)	(2.381)	(1.242)	(1.335)	(2.045)
Observations	112	112	112	112	112	112	112	112	112	112	112
R-squared	0.348	0.296	0.311	0.255	0.275	0.297	0.257	0.436	0.360	0.375	0.301

Robust standard errors are in parentheses.
*** p<0.01, ** p<0.05, and * p<0.1.