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Firm-level simulation of supply chain disruption triggered by actual and predicted earthquakes*

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Abstract

This paper reports simulations of supply chain disruptions regarding the Great East Japan Earthquake and the predicted Nankai Trough Earthquake. The simulations are based on the actual nationwide supply chains of Japan and on an agent-based model. As a result, we obtain the following findings. (1) Based on simulations of the Great East Japan Earthquake, we calibrate the parameters in the model. The result shows that the simulation reproduces the aftermath of the disaster well, which means the simulation captures the propagations of the damages and the recoveries from them on supply chains. (2) Indirect damages of both earthquakes geographically permeate the entire country in a quite short term. Additionally, the damages to firms show synchronized fluctuations due to the network structure. (3) Simulations of the Nankai Trough Earthquake show that direct damages are 12 times greater than those from the Great East Japan Earthquake, but indirect damages are approximately 4.5 times greater in a year. (4) By estimating indirect damage triggered by a single firm loss, approximately 10% of firms cause more than 10% damage of the entire supply chains.

Keywords: supply chain, propagation, disaster, agent, simulation, high performance computing
JEL classification: L14

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1. Introduction

When natural disasters affect some regions, the economic damage permeates the supply chain and causes disruptions [Sheffi and Rice, 2005]. Therefore, indirect damages are often greater than direct damages [Tierney, 1997, Pelling et al., 2002]. For example, when the Great East Japan Earthquake (hereafter GEJE) in 2011 affected firms on the northeast coast, many firms in Japan were unaffected at the time. However, not only the unaffected firms but also firms in foreign countries stopped their operations due to shortages of supplies. Another example is the floods in Thailand in 2011. Since Thailand is a large producer of hard-disk drives, many firms assembling personal computers had to stop globally. Because the indirect damages are serious, models to estimate these damages have attracted interest in the economic literature [Rose, 2004].

One major approach is based on input-output (IO) tables [Leontief, 1936], which are matrices of the input-output relations among different sectors in the economy. More precisely, IO tables show how much input from each sector is required to produce one dollar of production in a sector. IO tables have been used to estimate the effects of a shock in a sector on production in other sectors through inter-sectoral production relations [Haimes and Jiang, 2001, Santos and Haimes, 2004]. In particular, [Okuyama et al., 2004] examined using IO tables the indirect effects of natural disasters due to supply chain disruptions. Although earlier works relied on fixed IO tables before and after disasters, [Rose and Liao, 2005] incorporated flexible coefficients into IO tables by employing computable general equilibrium (CGE) models. In their model, the number of inputs required for production in a particular sector is endogenously determined in the model and thus can be changed after a shock.

However, this approach using IO tables is clearly insufficient to examine the propagation of negative shocks through supply chains because IO tables capture production relations at the sector level and not at the firm level [Haimes and Jiang, 2001]. In other words, although how indirect damages propagate through supply chains depends heavily on how directly damaged firms are connected to other firms [Hallegatte, 2008], such networks at the firm level are not captured by IO tables.

To overcome this shortcoming of models based on IO tables at the sector level, [Hallegatte, 2008] proposed an agent-based model in which firms, rather than sectors, interact with each other through supply chains. Using this model, this author simulated how damages due to a negative shock propagate through supply chains. However, because the author lacked actual data on supply chain relations among firms, hypothetical random networks were used, although they incorporate actual IO relations at the sectoral level into the model. In contrast, [Bak et al., 1993, Delli et al., 2005] utilized firm-level models but did not incorporate actual data.

The use of hypothetical networks, rather than actual ones, in simulation analysis is clearly a drawback because the network science literature has shown that a small difference in the network structure can lead to a substantial difference in the behaviors of agents in the network [Newman, 2010, Barabási, 2016]. Recently, the economics literature has also identified the role of the structure of firm networks in the propagation of negative shocks [Gabaix, 2011, Acemoglu et al., 2012]. Therefore, one might not obtain any reasonable conclusions about how damages in terms of production by natural disasters propagate through supply chains without using actual data from networks of firms in the economy. Such investigations have not been performed, although propagation of negative shocks through financial networks of firms has been modeled [Gieseckey and Weber, 2006, Battiston et al., 2007] and empirically examined using actual data [Fujiwara and Aoyama, 2010, De Masi et al., 2011].

Based on the above discussion, we conducted a series of simulations based on the nationwide supply chain in Japan, as well as a modified model of [Hallegatte, 2008] to tackle this issue. Using artificial disasters, not actual disasters, we clarified the features of the propagation regarding the data and the model. First, if we assume that the supply chain is the random network, which is widely used as a hypothetical supply chain, the outcome is totally different from the actual network, and it underestimates the indirect damage. Second, the heterogeneity of damages leads to different results. Intensive damages, i.e., larger damages to fewer firms, result in faster and greater propagation than extensive damages. Finally, the actual supply chain derives robustness from the substitution of intermediate supplies.

In contrast, there are several issues that have not yet been clarified in simulations. First, the results have been based on artificial disasters and have not included analyses of actual disasters. Second, recovery, which the actual economy undergoes, has not been considered. Finally, the models have had parameters, but the values have been arbitrarily decided. Therefore, simulations cannot surely estimate indirect damages caused by disasters.

To complement the missing parts of the analyses, we discuss actual and predicted disasters and estimate parameters in the model. As a result, we obtain the following findings. (1) Based on simulations of the GEJE, we calibrate parameters in the model. The result shows that the simulation reproduces the affected supply chains in the Japanese economy in the sense of propagations of damages and recoveries from them. (2) Indirect damages of both earthquakes geographically permeate the entire country. Additionally, the damages to firms show synchronized fluctuations due to the network structure. (3) Simulations of the Nankai Trough earthquake (hereafter NTE), which is predicted meticulously, result in damages 12 times larger than those of the GEJE, although indirect damages are 4.5 times larger. (4) By estimating indirect damage triggered by a single firm loss, approximately 10% of firms cause more than 10 % damage of the entire supply chain.

The remainder of this paper is organized as follows. Section 2 introduces the data. Section 3 describes the model used in our simulation analysis. Section 4 shows the simulation results and provides a discussion. Section 5 concludes the paper.

2. Data

The core data of this paper consist of a firm-level supply chain. Tokyo Shoko Research (TSR) collected the data every year based on questionnaires for firms. This investigation covers almost all of the active firms in Japan. Specifically, we use the TSR Company Information Database and the TSR Company Linkage Database collected in 2011 because we simulate the indirect damage of the GEJE. The databases are licensed to the Research Institute of Economy, Trade and Industry (RIETI). The data include detailed firm information. We use identifiers, addresses of headquarters, industrial classifications and sales among this information so that we can incorporate the data into simulations. We should note that, although the maximum number of suppliers and clients reported by each firm is 24, we can capture more than 24 suppliers and clients because a large firm is designated by many other firms as a supplier and client. Therefore, the number of suppliers and clients is not limited to 24. Actually, many firms have more than 1,000 relationships [Fujiwara and Aoyama, 2010]. The number of firms in the supply chain is 1,109,549, and the number of supplier-client relationships is 5,106,081. However, the numbers decrease based on the procedure described later.

We obtain the exact locations of firms from the addresses of their headquarters using the geocoding service provided by the Center for Spatial Information Science, the University of Tokyo. The locations are used especially to identify the directly damaged firms, which are necessary for the later sections. We should note that firms might have branches or factories at different addresses from the headquarters and that transactions occur between addresses. However, it is natural to acknowledge that the headquarters have significant functions of the firms. In addition, it seems that relationships between branches or factories change more often than the relationships between firms; hence, it is unrealistic to obtain and utilize the data. Therefore, it seems acceptable to use the addresses of headquarters when we identify the firms that are directly damaged.

Although the TSR data include information about who the suppliers and clients are, the relationship information does not include the values of transactions in each supplier-client tie. Since we need the values of ties, we estimate the values with the following two-step calculations. First, each supplier's sales are divided into clients as values (as purchases) proportional to the sales of the clients. This step provides each link with a tentative value. However, there are two shortcomings to the tentative values at this step. One comes from a lack of information about sales regarding final consumers, which is obviously not negligible for simulating the economy and is necessary for our simulations. The other shortcoming comes from the deviation compared to gross domestic product. Since our simulations can output production and the value added (gross domestic product), we can compare simulations with actual data, which is important for simulating the earthquakes and their aftermaths. Therefore, as a second step, we incorporate an IO table for Japan in 2011 obtained from [Ministry of Economy, Trade, and Industry, 2011]. Note that we use the IO table to adjust our values and not to conduct conventional analyses based on IO tables. As a concrete procedure, we aggregate transaction values at the sector level based on the industrial classifications of firms, i.e., from one sector to another. More specifically, the value of products from sector A sold to sector B, obtained from tentative values in the first step, is linearly multiplied so that the value fits a value in the IO table. Similarly, the value of the final consumption of products from sector A in the IO tables is proportionally divided among all of the suppliers in sector A in the TSR data using their sales. Through these two steps, the aggregate of the tie-level transaction values equals those from the IO tables. Some firms, however, do not have sales information, and the above procedures are not applicable. As a result, the final number of the firms is 887,715, and the final number of links is 3,223,137.

As a minor adjustment, industries are categorized by the Japan Standard Industrial Classification (JSIC) [Ministry of Internal Affairs and Communications, 2013] in the TSR data. The 1,460 classifications at the four-digit level of JSIC are converted into the 190 basic sector classifications of the IO tables.

The GEJE was the largest earthquake in Japanese history and the fourth largest earthquake in world history [Cabinet Office in Japan, 2012]. The magnitude was 9.0. The victims numbered more than 18,000 people (including missing persons). The estimation of the direct damage was 16.9 trillion yen (including buildings, lifelines, etc.).

Since the GEJE was an actual disaster, we can use the data related to direct damages and the aftermath to calibrate the model. As far as we know, there are no published data that exhaustively show how each firm sustained damage. Therefore, we combine several sources and create direct damage data for simulations. The important feature of the earthquake is a combination of disasters, i.e., the earthquake and the tsunami caused by the earthquake. Therefore, we separate the damaged areas into two types. One is affected by the tsunami (coast side), and the other is affected by the earthquake (inland). Although the coast side unmistakably experienced the earthquake, the tsunami damage was greater, and it is valid that we assign the coast side to the tsunami area. We refer to [Ministry of Internal Affairs and Communications, 2014] for the two areas. The left panel in Figure 1 shows the areas. The areas are at the municipal level.

Although the damage areas are separated into the inland and the coast side, the firms in these areas obviously did not experience uniform damage. In addition, the heterogeneity of the damage caused totally different outcomes [Inoue and Todo, 2017]. Therefore, each firm's damage is stochastically decided by a distribution based on the statistics [The Small and Medium Enterprise Agency, 2011]. Table 1 shows the distribution of the damages.

The heterogeneous damages of directly damaged firms are stochastically chosen based on the above areas and distributions. The left panel in Figure 2 is a sample of directly damaged firms and their volumes of damages for the GEJE. The damage is shown as the production capacity, which is explained in the next section. We can see that the firms on the coast side experience more serious damages than those inland.

The Nankai megathrust earthquake is a great earthquake that will occur along the fault line under the Nankai Trough. The fault line lies to the south of Honshu island (the main island of Japan). These earthquakes occur periodically at an interval of approximately 90 to 200 years. The probability of the next earthquake occurring is more than 70% over 30 years, and a typical estimation predicts that there will be victims of approximately 23 thousand people and economic losses of 95 billion yen [Cabinet Office in Japan, 2014]. The next earthquake has been multilaterally studied, including many different components and scenarios.

As is the case of the GEJE, we create maps of damaged areas. We incorporate the first report of the disaster management working group for the Nankai Trough Great earthquake [Cabinet Office in Japan, 2013]. It predicts the exact locations affected by an earthquake and tsunami. Among many scenarios, we choose a typical scenario. The predicted damage due to the earthquake and tsunami is provided by plots on the map. If a municipality has a plot greater than or equal to "seismic intensity 6 strong" on the Japanese scale, the municipality is assigned damage due to the earthquake. In addition, if a municipality has a plot of a tsunami higher than 5 m, the municipality is assigned damage due to the tsunami, and the assignment of the tsunami overrides that of the earthquake. The obtained map is shown in the right panel of Figure 1. The stochastically chosen firms are shown in the right panel of Figure 2. We can simulate the direct and indirect damages due to the next earthquake based on the detailed prediction given by the model and simulation, with the parameters calibrated by the GEJE.

3. Model

The model proposed by [Hallegatte, 2008] underlies our model, but we make several improvements. The model is an agent-based model. Agents, such as firms and final consumers, follow rules. There are no optimizations such as those imposed by the general equilibrium model. By the same token, firms do not have access to global information or the information of firms that are not adjacent to them. They only know the information of adjacent firms.

Each firm uses a variety of intermediates as inputs and delivers a specific product defined by the sector to which the firm belongs. The targets of delivery are other firms and final consumers. As a feature of the model, firms have inventories of intermediates to address possible supply shortages. However, there is no inventory for the products that they deliver. An overview of the model is provided in Figure 3, showing flows of products to and from firm i in sector r in particular.

We later consider a natural disaster that affects firms in the supply chain so that some products cannot meet demands due to direct or indirect damages. However, before considering disasters, we first describe the pre-disaster situation. The daily trade volume from supplier j to client i before the disaster is denoted by $A_{i,j}$, whereas the daily trade volume from firm i to final consumers is denoted as C_i. Then, the initial production of firm i in a day before the disaster is given by

$$P_{\mathrm{ini}i} = \sum_j A_{j,i} + C_i. \tag{1}$$

Henceforth, we consider the situation after a disaster. At time t=0, a disaster occurs. We assume that firm i has an inventory $S_{i,j}$ of the intermediate good produced by firm j and restores the inventory to a level equal to a given number of days n_i of utilization of product j. On day t, the orders from firm i to its supplier j, denoted as $O_{i,j}(t)$, is then given by

$$O_{i,j}(t) = A_{i,j}\frac{D_i^*(t-1)}{P_{\mathrm{ini}i}} + \frac{1}{\tau}\left(n_i A_{i,j}\frac{D_i^*(t-1)}{P_{\mathrm{ini}i}} - S_{i,j}(t)\right), \tag{2}$$

where $D_i^*(t-1)$ is a realized demand for firm i on day t-1, the previous day, and τ is the number of days to adjust its inventory size. For example, when τ is six, as we assume later in our simulations, firms plan to fill the gap between the projected inventory (i.e., n days of demand) and the actual inventory gradually. Concretely, firms make order for adjusting inventories by one sixth of the gap. The first term of the right-hand side of equation (2) is the amount of product j that is needed to satisfy the demand on the previous day. The second term indicates the amount of product j that is needed to restore the inventory to the projected level.

One might think that, if the economy is experiencing a disaster, the projected inventory is disregarded by the firm. However, since firms do not know whether they are involved in the disaster indirectly or not, including the degree of the effect, it is natural that they attempt to maintain the same level as their pre-disaster inventory size.

Accordingly, the total demand for product i on day t, $D_i(t)$, is given by the sum of the final demand from consumers and the total orders from its clients:

$$D_i(t) = C_i + \sum_j O_{j,i}(t). \tag{3}$$

Here, we consider a disaster affects the economy and damages firm i directly. We assume that a certain proportion, δ_i(t), of production capital of firm i is destroyed by the disaster. Then, the production capacity of firm i, $P_{\mathrm{cap}i}$(t), or its maximum production assuming no supply shortage is given by

$$P_{\mathrm{cap}i}(t) = P_{\mathrm{ini}i}(1 - \delta_i(t)). \tag{4}$$

The production of firms might also be limited by shortages of supplies. Because we assume that firms in the same sector produce the same product, shortages of supplies from firm j in sector s can be compensated for by supplies from firm k in the same sector (Figure 3). In other words, we do not assume changes in supply chain ties after the disaster. Thus, the total inventory of product s in firm i on day t is

$$S_{\mathrm{tot}j,s}(t) = \sum_{j \in s} S_{i,j}(t). \tag{5}$$

Initial consumption of product s at firm i is also defined for convenience.

$$A_{\mathrm{tot}i,s} = \sum\nolimits_{j \in s} A_{i,j}. \tag{6}$$

Using the above two variables, $P_{\mathrm{pro}i,s}(t)$, maximum production for firm i limited by the inventory of product s on day t is obtained as follows.

$$P_{\mathrm{pro}i,s}(t) = \frac{S_{\mathrm{tot}j,s}(t)}{A_{\mathrm{tot}i,s}} P_{\mathrm{ini}i}. \tag{7}$$

Then, we can determine the maximum production of firm i on day t, considering its production capacity, $P_{\mathrm{cap}i}$, and its production constraints due to shortages of suppliers, $P_{\mathrm{pro}i,s}(t)$:

$$P_{\mathrm{max}i}(t) = \mathrm{Min}\left(P_{\mathrm{cap}i}(t), \mathrm{Min}_s\left(P_{\mathrm{pro}i,s}(t)\right)\right). \tag{8}$$

Actual production of firm i on day t is, therefore, given by

$$P_{\mathrm{act}i}(t) = \mathrm{Min}\big(P_{\mathrm{max}i}(t), D_i(t)\big). \tag{9}$$

When the demand for a firm is greater than its production capacity, the firm cannot completely satisfy its demand, as denoted by equation (9). In this case, firms should ration their production to their clients. [Hallegatte, 2008] proposed a rationing policy in which each client firm and the final consumers receive the number of products in the same proportions ($P_{\mathrm{act}i}/P_{\mathrm{ini}}$) as its pre-disaster trade volume. However, this allocation might not be the case in practice. For example, if we suppose that client h of firm i in sector r increases its demand for product r after the disaster because other suppliers of product r for client h are destroyed, then according to this rationing policy, firm i will decrease the supply of product r to other firms, although these firms are not affected directly by the disaster or affected indirectly by their suppliers. Thus, this rationing policy is most likely to augment the propagation of negative shocks, leading to overvaluation of the effects of disasters. For example, 10% damages ($\delta = 0.1$) for firms can result in complete incapability of the supply chain network, which might not occur in the actual economy.

Therefore, for our improvement, we employ another rationing policy, in which firms are prioritized according to the level of order after the disaster relative to their initial order. Note that we do not have to consider a rationing policy if the production capacity is greater than the demand.

We explain this improved policy more concretely. We suppose that firm i producing r has two client firms, g and h, and a final consumer (see Figure 3). In addition, because of disasters, we suppose that firm i has two clients g and h, and importantly, product r from firm i cannot fill their demand. Let's consider that the ratios of post-disaster orders to pre-disaster orders (hereafter, the post-to-pre-order ratio) are 0.6 and 0.7 for firms g and h, respectively. In contrast, the corresponding ratio for final consumers remains one. As a first step, firm i calculates the minimum post-to-pre order ratio among all of its clients and the final consumer. The minimum ratio is 0.6 for firm g in this case. This minimum ratio is applied to all of the clients and the final consumer. In this case, 0.6 is applier for firm g and h, and the final consumer. Now, if the total demand obtained by applying the minimum ratio is greater than firm i's remaining production capacity, firm i distributes its product to all of the clients and the final consumer equally. In this case, the rationing process is completed. On the other hand, if the total demand is smaller than firm i's remaining production capacity, firm i first fulfill the demand with the minimum ratio for all the clients and the final consumer. In the current case, the minimum ratio, 0.6 is fulfilled for client g and h, and the final consumer. Now, although the demand from the client with the minimum post-to-pre order ratio is fully met, the demand from other clients remains. In the current case, 0 for client g, 0.1 for client h, and 0.4 for the final cosumer remain. Thus, we follow the same procedure from the beginning until the remaining production capacity is completely used to the clients and final consumers.

Following the rationing policy, the realized total demand for firm i, $D_i^*(t)$, is then given by

$$D_i^*(t) = C_i^* + \sum_j O_{i,j}^*(t)_{j,i}, \tag{10}$$

where the realized order from firm i to supplier j is denoted as $O_{i,j}^*(t)$, and the realized demand from final consumers is C_i^*. Accordingly, the inventory of firm j's product in firm i is modified to

$$S_{j,i}(t+1) = S_{j,i}(t) + O_{j,i}^*(t) - A_{j,i}\frac{P_{\mathrm{act}j}(t-1)}{P_{\mathrm{ini}j}}. \tag{11}$$

Thus far, the model does not have a recovery mechanism to disasters. However, the actual economy reacts to malfunction. For example, a firm can switch or add a supplier or client because it cannot buy or sell products. Another example is over-production. If a firm receives more demand than the pre-disaster level, it can react to the demand by producing more, which might be accomplished by asking workers on overtime or by hiring temporary workers. Other than the above examples, there might be other reactions. However, it is not realistic to consider all of them. For simplification, we introduce a simple reaction in this study. A firm that is directly damaged stops for σ days and then recovers γ in ratio, that is,

$$\delta_i(t) = (1-\zeta\gamma)\delta_i(t-1), \tag{1}$$

where ζ is a damping factor. ζ is a ratio of healthy neighbors to neighbors. Therefore, for example, if no neighbors of firm i do not sustain direct damages (including already recovered firms), $\zeta = 1$. On the contrary, if all neighbors still sustain direct damages, $\zeta = 0$. This damping factor is introduced on the basis of the empirical finding of resilience. Concretely, in the GEJE, damaged firms recovered fast if they have transaction partners outside damaged areas [Todo et al., 2015]. Note that this recovery model is introduced by us.

Using the model above, we simulate how direct damages due to a natural disaster, represented by an exogenous reduction in production capacity of a set of firms, affect the production of the whole economy through the propagation of negative shocks along supply chains. In the simulation, we utilize the actual supply chains of firms in Japan, obtained from the TSR data. $A_{j,i}$ and C_i are determined from the IO tables and the supply chain ties, as described in Section 2. We assume that τ is six, whereas n_i, σ, and γ are parameters in the simulations to fit the actual economic reaction.

In each simulation, exogenous damages are given on day 0. The damage to each firm is decided by the procedure explained in Section 2. Then, we examine how the sum of value added (or the value of production less the total value of intermediates used for the production) of all of the firms in the economy changes over time. For each set of parameter values, we simulate 30 times and show the results graphically.

Because the simulation in this study requires substantial computational power due to including 887,715 agents and 3,223,137 ties, we utilize a supercomputer and run simulations in parallel to reduce the run time. Since the simulation can be executed independently for each trial, it can be categorized into so-called embarrassingly parallel simulation, and the parallel execution reduces the consumption of wall time without loss. The simulation code is shared on GitHub so that the reader can run his or her own agents and networks. The code provides abundant variations of simulations. See details on the Web site.[2]

4. Simulation Results and Discussions

4.1 The Great East Japan Earthquake

First, we discuss simulations of the Great East Japan Earthquake. As described in Section 3, we create the directly damaged firms based on the distributions. The average of the total direct (initial) damages over 30 sets is 1,721 million yen in value added per day. (If the damage is not propagated or recovered, the damage per year is 628 billion yen.)

Figure 4 shows the results of the simulations. The pink plots are the industrial production index. To see the actual economy's reactions, we incorporate the index. The industrial production index is adjusted so that the value is comparable to the value added of the simulations, i.e., to GDP.

The reason why we do not use the GDP straightforwardly is that it is reported quarterly. Actually, we do not see the change in GDP after the earthquake. This is natural because it includes every effect of reactions such as emergent imports, fiscal actions, and also business cycles. To address this problem, we use the industrial production index. Because it covers the value added of the mining and manufacturing industries and it seems that they reflect the domestic production level. However, since these industries seem susceptible to supply chain disruptions, we should note that the production cutback might be overestimated. In addition, the actual firms speculate current and future situations, so they might withhold their productions. (In contrast, the model has only limited information.)

The red line in Figure 4 shows the simulation results without the recovery. The inventory size of firms (n_i)has a Poisson distribution with a 10 day average. It decreases to almost zero value added. This is because the damage permeates the entire supply chain. Importantly, the propagation is rapid, which arises from the path lengths of supply chains between any two firms being very short.

2 https://github.com/HiroyasuInoue/ProductionNetworkSimulator

Therefore, a damage can transfer in a very short time. In the network science literature, the network has a power-law distribution is called a scale-free network [Barabási, 2016] and the supply chain is applicable for it. The scale-free network has ultra-small-world properties, and the average path length of the network follows $\ln \ln N$, where N is the number of nodes. Because of the rapid propagation, it is important to aid firms immediately after disasters. In addition, from the comparison with the industrial production index, the actual system has very strong recovery.

The green line in Figure 4 indicates the result based on IO table. We apply the same direct damage of the simulations and convert them to sectoral decrease of demand. Then, by using Leontief's inverse matrix, we calculate the total propagated damages among sectors. The green line is horizontal between day 1 to day 365 because we cannot know the propagation along the time. As the green line shows, it can be understood that the IO table underestimate the damage. This is because it does not consider the constraint of the necessary intermediate goods.

The blue line in Figure 4 indicates the simulations with calibrated parameters so that the line fits the industrial production index. Here, the parameters are the inventory size, the stop day and the recovery day. As a result of the parameter searches explained later, we obtain 9 days for the inventory size (n_i) (the average of the Poisson distribution), 6 days for the stop day (σ) and 0.025 for the recovery ratio (γ).

We see some gaps between the blue line and the pink plots, especially around the first and second plots of the industrial production index. This can be understood that the industrial production index captured withholding of productions after the disaster. That is, firms produce less to avoid to have too much unsold products. Therefore, comprehensively, it can be said that the model replicate the indirect effect of the disaster well.

Here, we interprete the calibrated simulations, especially about the recovery ratio. The supply chain in the Japanese economy has recovering capacity equivalent to the recovery that firms regenerate by the ratio of 0.025 ($\gamma = 0.025$). If there is no damping factor, it means 50% of the damage recovers in 28 days, and 90% of the damage recovers in 91 days. This term seems short because aid from government, such as financing and taxes, lasts more than one year. The discrepancy might be due to our simple assumption of the recovery, namely all of directly damaged firms have the same ratio to recover. There should naturally be the diversity in the recovery days between firms. Indeed, the questionnaires collected by Teikoku Data Bank state that there are wide ranges of diversity, and some firms exit from business. Therefore, some of them require a long time to recover, and the aid by government should consider them.

The calibrations of the paramters are conducted as follows. The parameters of the model are calibrated by fitting the simulation outputs and using the industrial production index. The search space is a grid. The parameter search ranges from 1 to 20 for the inventory size, from 0 to 20 for the stop day, and from 0.005 to 0.100 for the recovery ratio. The step sizes are 1, 1, and 0.005, respectively, and all combinations of the three parameters are tested. Figure 5 shows all of the simulations of the parameter search. Based on the results, the squared error is calculated at the point when the industrial production index of each month is plotted, and the summation of them is considered an evaluation (error) of the parameters. The best parameters are 9 for the inventory size, 6 for the stop day, and 0.025 for the recovery ratio.

We plot the direct and indirect damages on the geographical maps on a daily basis. The calibrated parameters are used for this step. A sample at day 15 is shown in the left panel of Figure 6. (We have uploaded a video of the simulation to the Web[3].) Day 15 is chosen because it clealy shows how the direct damages are propagated to the entire country in such a shot term.

We find two indications from the time-series geographical plots. The first finding is the rapid spread across the geography. The disaster occurs locally, but it spreads across the country immediately, indicating that many firms adjacent to directly damaged firms are geographically distant. Obviously, the supply chain has local agglomeration, but simultaneously, it has long-distance connections. The second finding is the widely synchronized fluctuations of damages. That is, the damages to many firms increase and decrease simultaneously. This outcome can be understood from a giant strongly connected component that the supply chain has, and it covers 49.7% of firms. A giant strongly connected component indicates that any two nodes can traverse through links to each other. In addition, in the giant strongly connected component of this supply chain, there are numerous loops that cause non-linear behaviors and fluctuations. In the network science literature, the network is categoraized into the connected regime [Barabási, 2016], where the small-world behavior emerges.

4.2 The Nankai Trough Earthquake

Next, we discuss the NTE. The initial damages are created by following the procedure described in Section 2. The average of the total direct (initial) damages over 30 datasets is 21,344 million yen in the value added per day. This amount is 12 times larger than the that from the GEJE. The difference in direct damages can be seen as a number of plots in Figure 2. Since there are many manufacturing firms on the side of the Pacific Ocean, the direct damage is substantially large.

Figure 7 shows the simulation results. The red line indicates the simulations for the GEJE, and the blue line is for the NTE. The parameters calibrated by the GEJE are used for the simulation for NTE. We can see that approximately 30% of the output is impaired in NTE at the maximum level. Using the summations of the losses compared to the pre-disaster value added, we calculate the total damage of the disaster in a year. The total damage of the GEJE is 11,443 billion yen, and that of NTE is 51,999 billion yen. The ratio is 4.5. On the other hand, the ratio of the direct damage was 12. Therefore, the magnitude of the direct damage does not scale linearly to the indirect damage. This is mainly because indirectly damaged firms overlap through the propagation, especially downstream.

[3] https://youtu.be/XzRHSFHYKGA

If a firm cannot obtain a necessary intermediate to produce, there is no difference even if other intermediates cannot be obtained. As discussed in Section 4.1, the network has the giant strongly connected component, and it has numerous loops. Therefore, the overlaps seem to frequently occur.

We see a kink and a plateau at around 70 day. In addition, it was not obvious but the GTE has a similar stagnation of the recovery. It mainly comes from the damping factor. First, the damaged firms with firms without damaged firms recover (before the stagnations). At this moment, the remaining damaged firms seem to be densely connected and show slow recovery. However, as long as some of them are connected to non-damaged firms, the system recovers in the end.

We plot the damage from the NTE on the geographical map and see the change in the time series. The example of day 15 is shown in the right panel of Figure 6. (We have uploaded a video of the NTE simulation to the Web[4].) We see the damages immediately propagate throughout the entire country. It is also seen that more firms are affected than the number affected by the GEJE.

4.3 Single firm loss

In the previous simulations, we discussed the actual and predicted earthquakes. However, we can create any artificial scenario by adding damages into the supply chain. Regarding such artificial disasters, we have simulated many scenarios before [Inoue and Todo, 2017]. These simulations are about heterogeneous shocks, network structures, substitutes, regions and industries. In these simulations, randomly chosen firms experience damages.

As a complement to the scenarios, it is beneficial to know how a single firm loss will affect the entire economy. That is, a single firm might cause substantial damage to the entire economy or might not.

We simulate 7,332 cases with different firms. The number of samples was decided by computational resources. In a simulation, only one firm is completely destroyed at once. The influence of the simulation is calculated by (the summation of lost value added in a year) / (the summation of value added without damages in a year). We call this value system damage henceforth. Theoretically, the system damage can range from 0 to 1. Firms experience no recovery in the simulations.

Figure 8 shows the histogram of the system damage. Surprisingly, more than 90% of firms show less than 0.1 system damage. Concretely, 86.6% of sampled firms experience less than 10^{-5} system damage. If we consider the small-world property of the network and no recovery of firms, it can be said that the supply chain has strong robustness. Importantly, the robustness comes from substitutes. Conversely, 10% of firms cause serious system damage.

4 https://youtu.be/FuHEVxOudiQ

We check the Kendall correlation coefficients between the system damage and other variables for each firm. The variables are degree (number of suppliers and clients), in-degree (number of suppliers), out-degree (number of clients), amount of labor, number of institutes, number of factories, sales, and capital. The degree is 0.326, which is the largest, and the out-degree is 0.325, which is the second largest. In contrast, the-in degree is 0.239, indicating that a supplier with some number of clients has more risk than a client with the same number of suppliers. This finding corresponds to, in the short term, the downstream shock being more serious than the upstream shock, as described in our simulation.

5. Conclusion

We used the nationwide supply-chain network data of Japan, simulated the GEJE and calibrated the parameters of a modified model from [Hallegatte, 2008]. With the parameters, we examined the predicted NTE. As a result, we obtained the following findings. (1) The simulation result of the GETE finely reproduces the affected supply chains in the Japanese economy in the sense of propagations of damages and recoveries from them. (2) Indirect damages of both earthquakes geographically permeate the entire country in a quite short term. Additionally, the damages to firms show synchronized fluctuations due to the network structure. (3) The simulations of NTE show that direct damages are 12 times greater than those from the GETE, but indirect damages are approximately 4.5 times greater in a year. (4) By estimating indirect damage triggered by a single firm loss, approximately 10% of firms cause more than 10 % damage of the entire supply chain.

This study has much potential for enhancement. The recovery mechanism introduced in the model was very simple, but switching suppliers/clients is a potent measure as discussed. Actually, after the GEJE, it is known that firms enhanced the OEM agreements by which they could accommodate each other regarding necessary products. Since we have network data from after the disaster, we can observe and incorporate the actions. Another future work is to use global supply chain data. Since some countries have stronger community structures (a densely connected component of supply chains) than other countries have, it is expected that we would see different behaviors of propagations; therefore, we could measure different risks starting from each country. In addition, we could refine the simulation of the GEJE by considering the reduced power supply, mainly caused by the stoppage of the Fukushima Nuclear Power Station. Finally, as Otto et al. proposed [Otto et al., 2017], the model could incorporate price mechanisms so that we could consider markets.

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Table 1: Distribution of destruction. These data are for the coast side and inland. Data from [The Small and Medium Enterprise Agency, 2011].

	Complete destruction	Partial destruction	Some destruction
Coast side	54.4%	12.7%	28.7%
Inland	2.5%	2.7%	82.7%

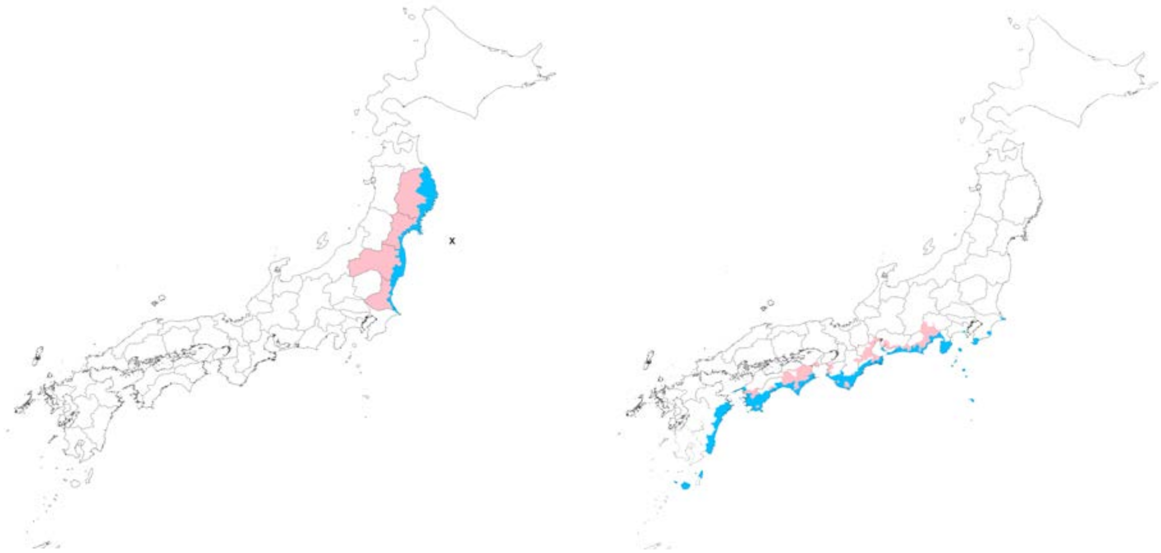

Figure 1: Actual and predicted areas damaged by earthquakes. Left: Actual areas damaged by the Great East Japan Earthquake. Areas damaged by earthquakes are colored pink. Tsunami damage areas are colored blue. X indicates is the epicenter. Right: Predicted areas damaged by the next Nankai Trough earthquake. The colors have the same meanings.

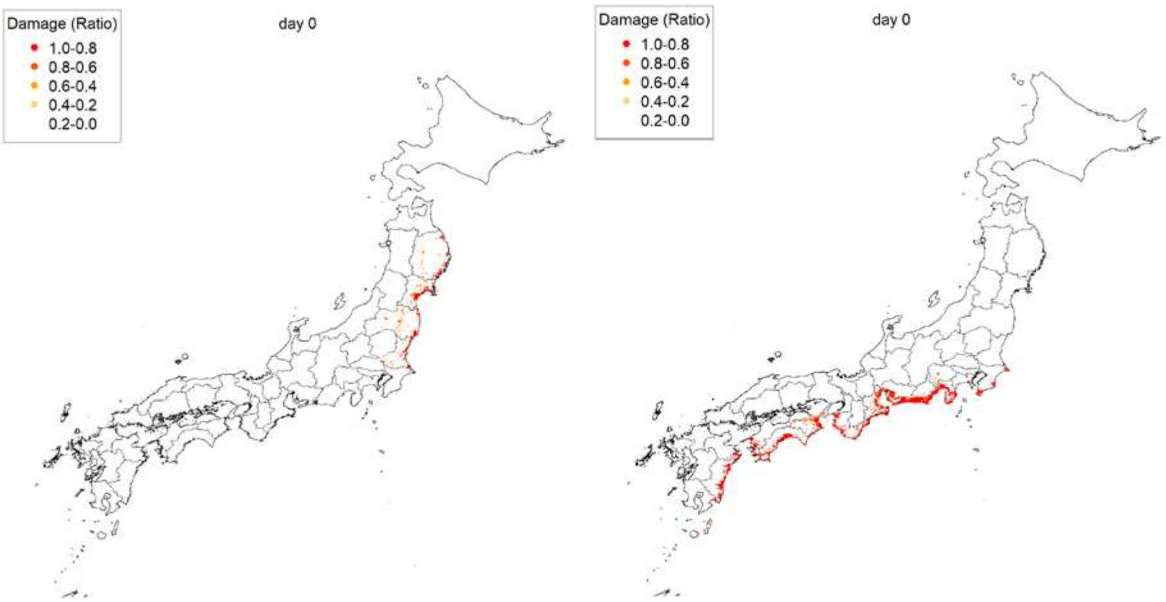

Figure 2: Samples of damaged firms chosen stochastically. Left: A sample from the Great East Japan Earthquake. Right: A sample from the prediction of the next Nankai Trough earthquake. Based on the distribution of damage, damages is assigned to firms stochastically. We see that the firms on the coast side are seriously damaged.

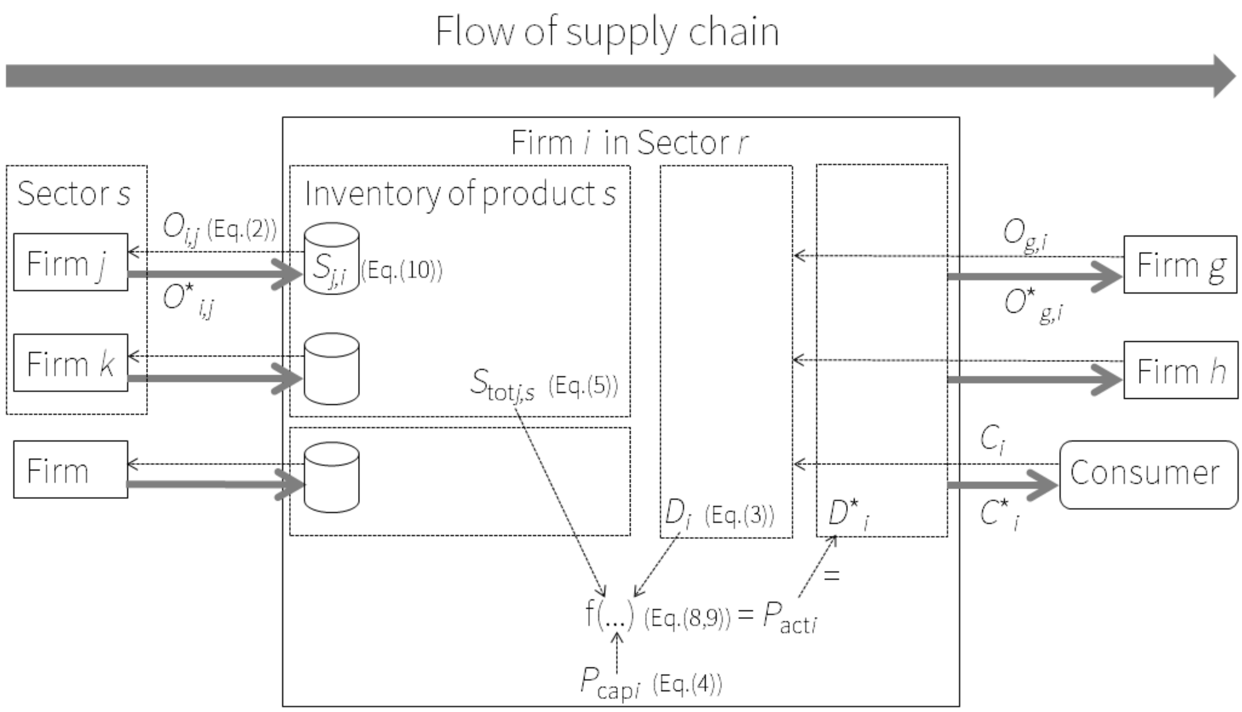

Figure 3: Overview of model. The flow of the product is from left to right, but orders have the opposite directions. Most equations are embedded with reference numbers. Inventories correspond to each product. Actual production is a function of product inventories, production capacity, and demand. The actual production is equal to the realized demand (from [Inoue and Todo, 2017]).

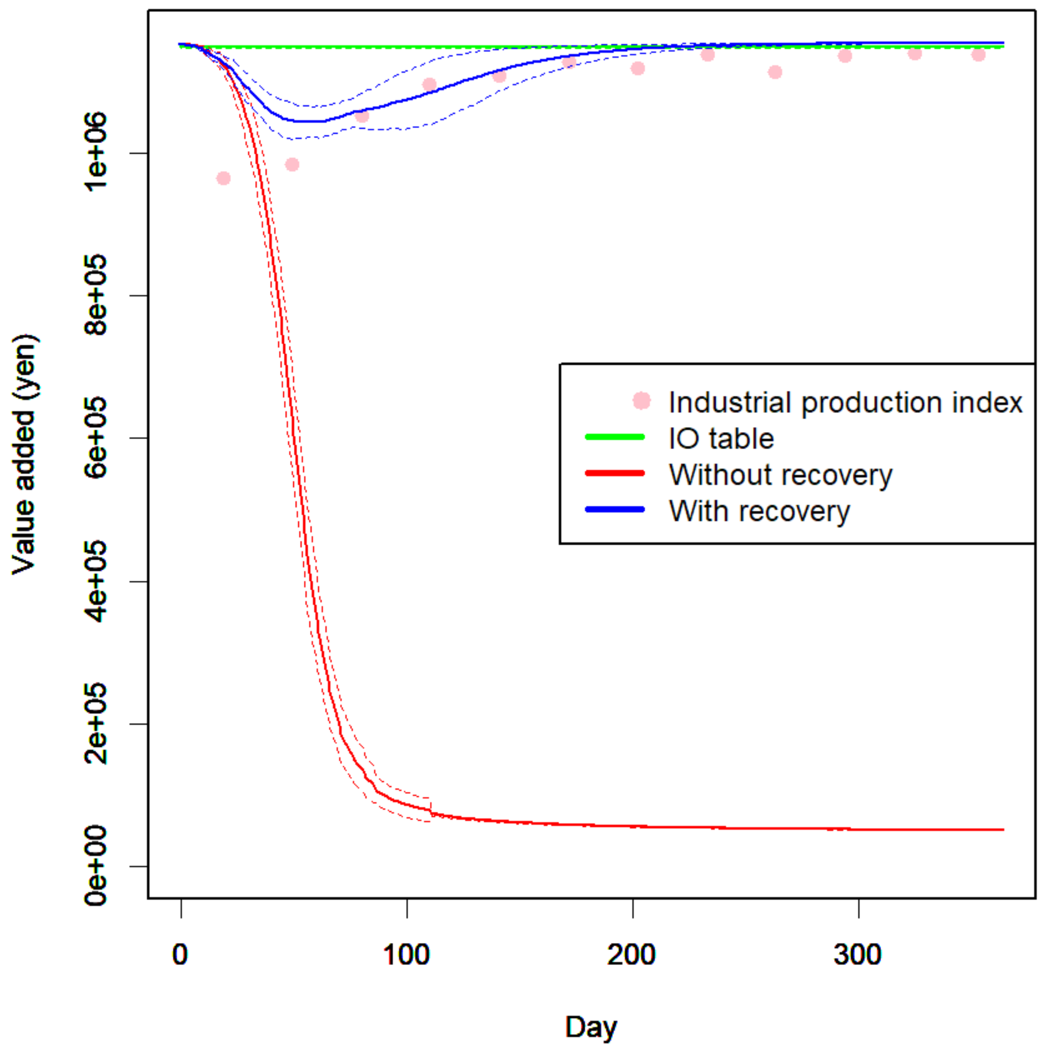

Figure 4: The Great East Japan Earthquake simulation and calibration. The horizontal axis shows days. The vertical axis shows the total value added in yen. The pink dots show the industrial production index. Since the index is published every month, the dots are placed on the last day of the month.

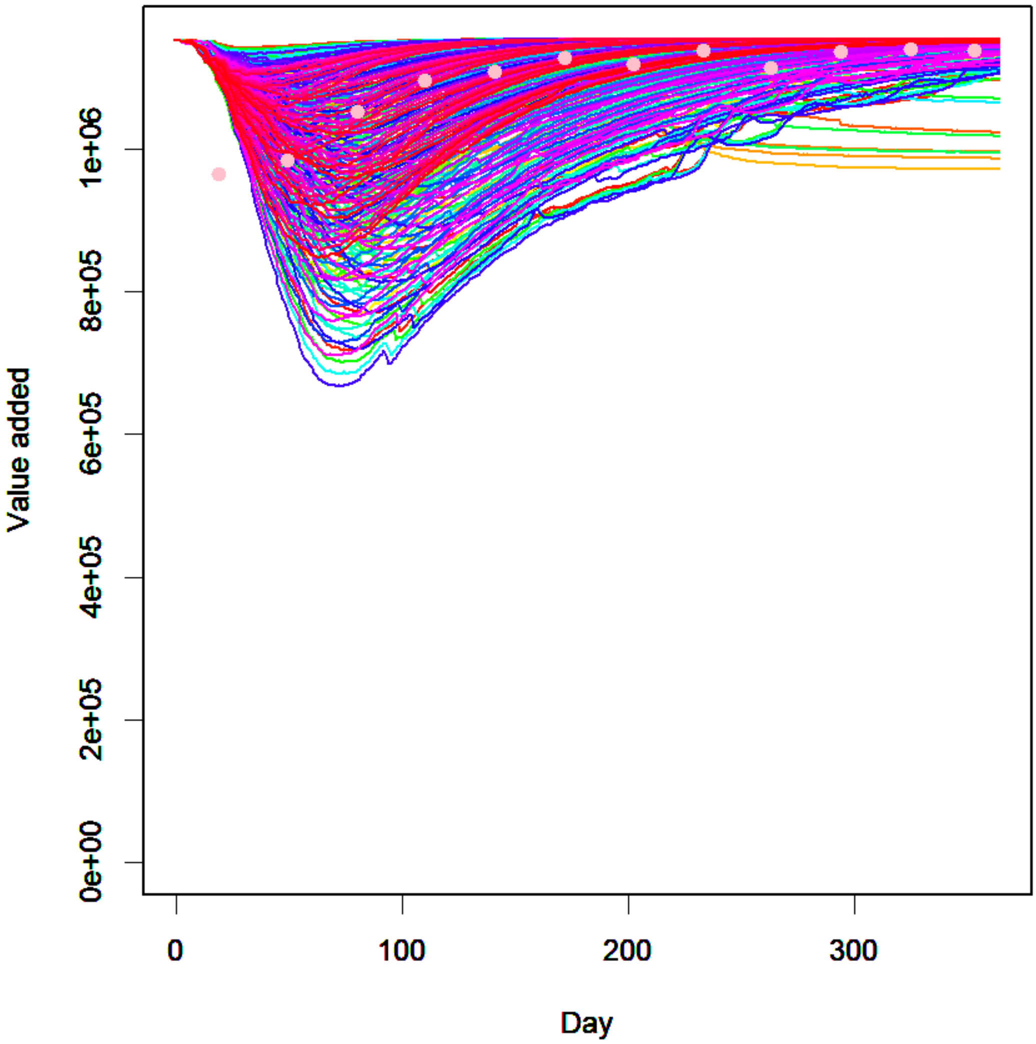

Figure 5: All simulations of parameter calibration: the parameters are inventory size, stop day, and recovery day. Errors are calculated between industrial production indices and simulations.

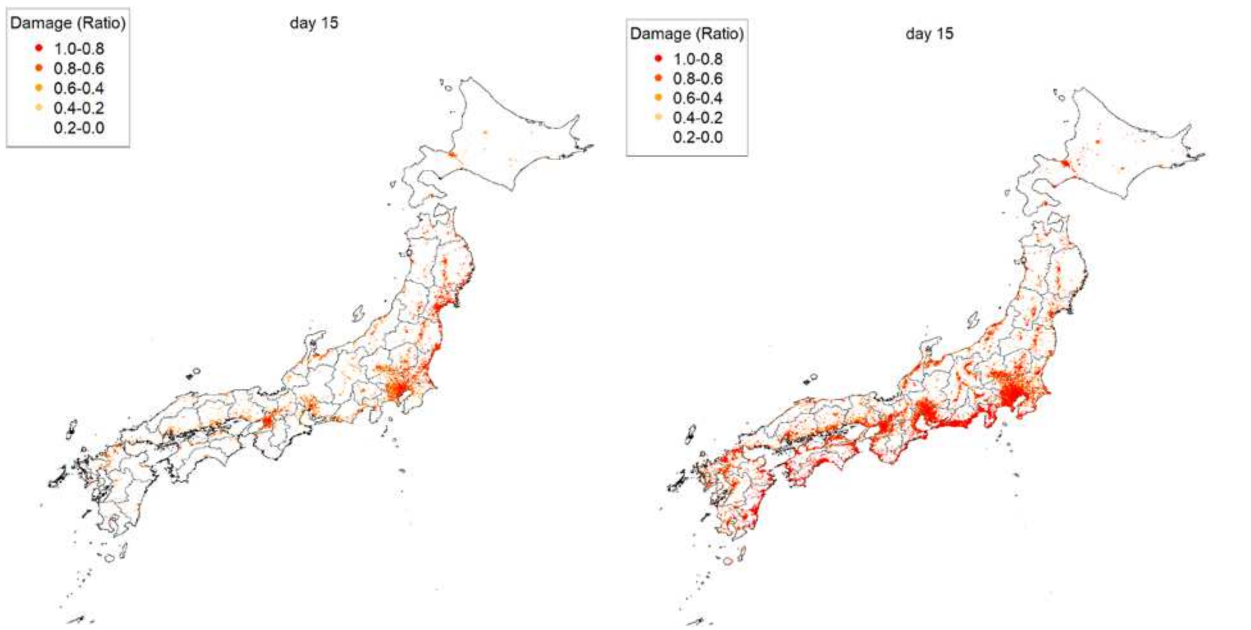

Figure 6: Geographic plots of damage. Left figure is the damage on day 15 caused by the Great East Japan Earthquake. Right figure is from the Nankai Trough Earthquake. These images are derived from the initial direct damages depicted in Figure 2.

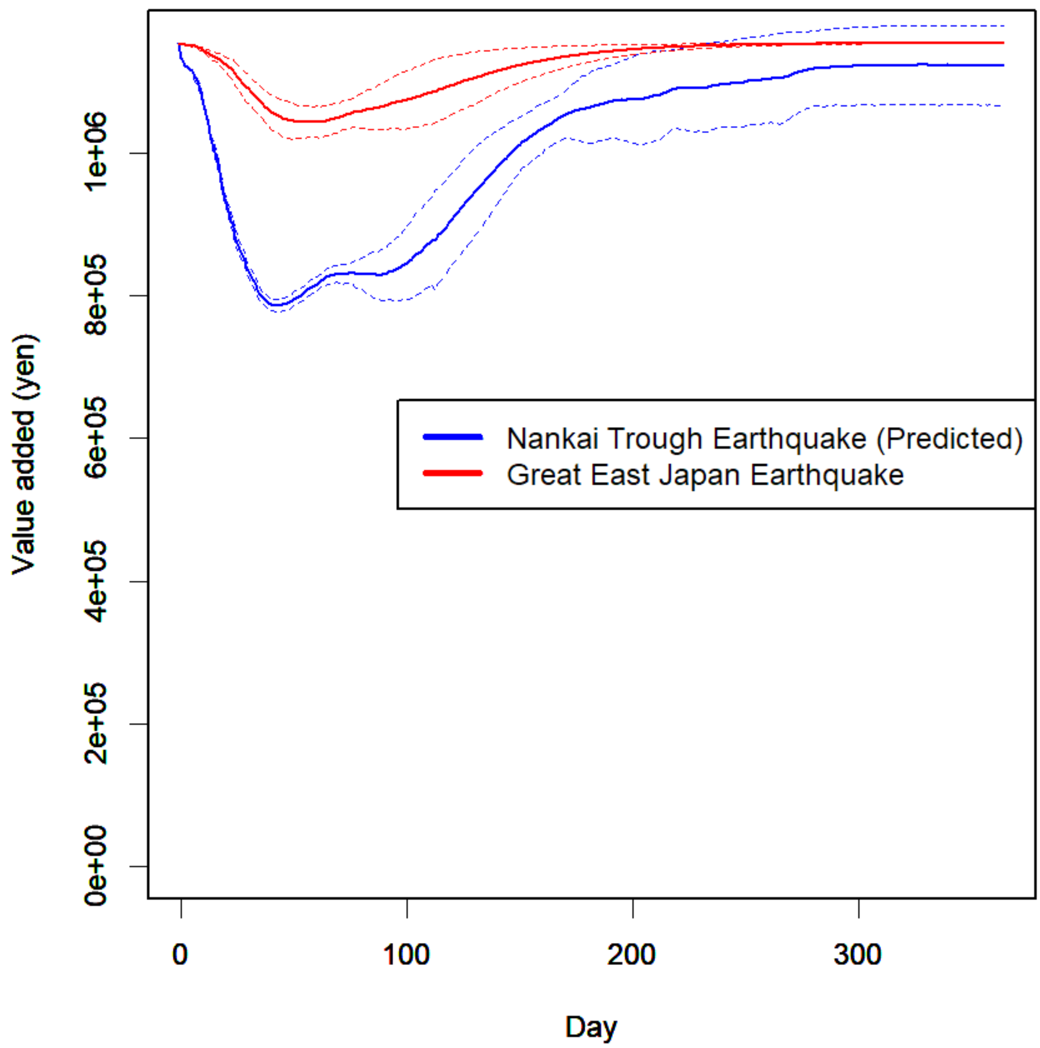

Figure 7: Comparison of the predicted Nankai Trough Earthquake and the Great East Japan Earthquake: the meanings of the axes are the same as in Figure 4.

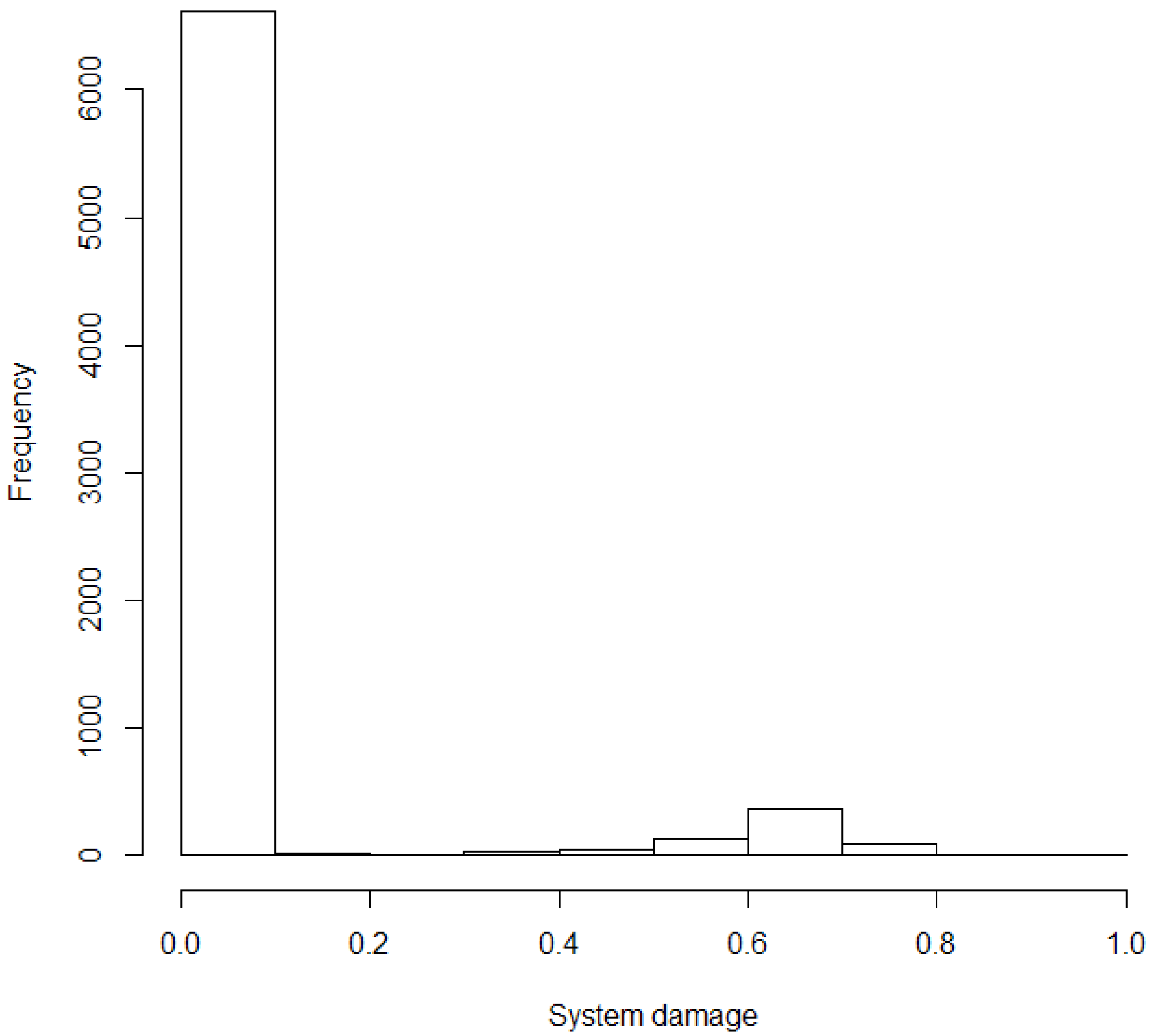

Figure 8: Histogram of system damage: horizontal axis is delimited by 0.1.