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A Model of Stratified Production Process and Spatial Risk

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Abstract In 2011, Japanese firms suffered severe losses as a result of the Great East Japan Earthquake and the Thailand floods. The firms incurred damage continually because they depended on spatially dispersed supply chains. Final goods producers are essentially attracted to outsourcing because of the prevailing scale economy in modern machinery industries. In addition, certain firms have dispersed their plants to different locations to avoid risks from powerful earthquakes that are expected near most of the developed metropolitan areas in the region. Such a strategy, however, has ironically caused contiguous damage to these firms. To capture the characteristics of supply chain over space and the cascade of spatial risks, we set up a two-level structure of circles where firms can be categorized. The top circle is occupied by intermediate goods producers, who provide differentiated inputs for the final goods producers in the second circle. We assume that scale economy works with respect to the variety of intermediate goods. Thus, final goods producers purchase inputs from intermediate goods producers located in different places, while paying transport costs in the process. We then evaluate the two-level structure in terms of location-specific hazards such as earthquakes. A more dispersed supply chain corresponds to a greater likelihood that final goods producers would suffer losses from the spatial risk. Simulation results reveal that the expected damage may be less for intermediate goods producers with more dispersed locations. On the contrary, final goods producers may be better served being spatially concentrated.

Keywords Fragmentation · Supply chain · Location risk · Economic resilience · Hazards · Disasters

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1 Introduction

Natural disasters cause human losses and economic damage.[1] The Great East Japan Earthquake in March 11, 2011 caused a total of 21,613 cases of fatalities and missing people (Fire and Disaster Management Agency, Japan 2014). With regard to economic damage, Tokui et al. (2012) estimated that the damage of the earthquake amounted to 1.35 % of the Japanese GDP.

Although the present paper focuses on the economic consequences of these disasters, recovery from such damage is an important aspect to consider. The concept of "resilience" is often used to evaluate the possible ways of recovery from such disasters. "Resilience" comes from the Latin word "*resilíre*," which means "to leap back," although the term also has many other definitions in literature (e.g., the survey of Omer 2013). Rose (2007) classified economic resilience into two concepts, namely, static and dynamic, with respect to time dimension. Static resilience pertains to maximizing the available resources at a given point in time, whereas dynamic resilience focuses on the speed of recovery or reconstruction. Hallegatte (2014) recently proposed similar groupings, namely, instantaneous resilience and dynamic resilience. These groupings are further categorized into macroeconomic and microeconomic resilience; the latter was further used to describe the distribution of losses across different areas of the society, such as households. In view of the groupings proposed by Hallegatte, the present paper analyzes the static/instantaneous resilience of an economy, with emphasis on the conflict of interest among producers. The details of our concern are explained below.

The interrelation between economic resilience and the geographic distribution of economic activities is important to examine. Davis and Weinstein (2002) found that the distribution of the regional population in Japan is robust, even during large man-made disasters (e.g., the Allied bombing of Japanese cities in WWII). More recently, however, the patterns of trade and the configuration of existing supply chains are changing drastically, along with the progress of globalization. Final goods producers are essentially attracted to outsourcing because of the prevailing scale economy based on modularity, particularly in modern machinery industries (Clark and Baldwin 2000). On the one hand, the fragmentation of foreign and domestic trade proceeds as a dispersion or disintegration force (Feenstra 1998; Kimura and Kiyota 2004). This fragmentation means that firms seek global comparative advantages in terms of individual parts or modules. As a result, secondary or tertiary subcontractors sometimes provide distinctive or unrivaled parts independently.[2]

On the other hand, in Japan for example, a number of firms have dispersed their plants to rural regions to avoid potential risks brought about by strong earthquakes anticipated around Tokyo or Nagoya (i.e., most developed metropolitan areas). Such a strategy, however, might ironically cause contiguous damage to these firms. In fact, in 2011, Japanese firms suffered great losses not only from the Great East Japan Earthquake but also from the Thailand floods, which caused considerably more damage than

[1] While Wisner et al. (2004) proposed the definition of disaster or disaster risk because of the interaction between vulnerability and hazards, the World Bank and United Nations (2010) adopted a similar definition. A hazard is a natural or man-made phenomenon capable of inflicting harm on communities (Gilbert 2013).

[2] According to Acemoglu et al. (2010), most firms in a supply chain with several levels do not recognize the actual relationships they have with one another.

the anticipated earthquakes around the metropolitan areas where majority of plants of these firms were originally located. The firms continually incurred damage because they depended on spatially dispersed supply chains. In Japan's automobile industry, for example, the production of automobiles was greatly damaged by both the Great East Japan Earthquake and the Thailand floods (Fig. 1). The total probability of risks becomes higher because each dispersed plant location faces a relatively positive probability of spatial risks such as earthquakes, floods, or political conflicts. If we connect the components of the supply chain, risks and even financial crises can be easily diffused. For example, Toyota Motor Corporation halted automobile production in all of its domestic plants from March 14 to 26, 2011 because of the disruption in the company's supply chain, thereby generating an output loss of 140,000 cars. Furthermore, the Thailand floods cost them 260,000 cars (Toyota Motor Corporation 2012, Part 3). Another example of a firm whose supply chain was disrupted by the earthquake is the Renesas Electronics Corporation. As a result of the collapse of certain plants of this semiconductor company, which also produces microcontrollers and microprocessors, many automobile companies (including General Motors in the US) were forced to cease production for a particular period. This incident is called "Renesas Shock," where certain subcontractors were noticed to have monopolistic powers, based on increasing returns to scale in recent supply chains as described above.[3]

The present paper analyzes the static/instantaneous resilience of a spatially dispersed supply chain network, with emphasis on the conflict of interest among producers. To do this, we established a simple model of spatial economy where firms are categorized to capture the ideal characteristics of the supply chain over space and the cascade of spatial risks. Then, we evaluate the structure or distribution of producers in terms of location-specific hazards such as earthquakes. By performing numerical simulations of possible backup within the supply chain, we can show that dispersion may be helpful for the intermediate goods sector but detrimental for the final goods sector. Therefore, intermediate goods producers with more dispersed locations, when final goods producers are also dispersed, may expect less damage. By contrast, final goods producers may be better off being concentrated spatially, according to the simulation results. Moreover, if we assume that such hazards also damage transportation in the supply chain, the loss is more significant for final goods producers than for intermediate goods producers. Although our model is very simple, the results are consistent with the empirical findings of Altay and Ramirez (2010).

The reminder of this paper is organized as follows. In Section 2, we briefly review the literature on the positive and negative aspects of resilience in a supply chain network. In Section 3, our model is described by the basic settings and spatial configurations of the firms considered in the current study. The results of our simulation are presented and examined in Section 4. Section 5 presents the conclusion.

2 A Brief Literature Review: Supply Chain and Its Resilience

In empirical studies, positive and negative aspects of resilience and spatial dispersion of production processes are present in a supply chain network. The positive aspect is as

[3] See ESCAP (2013, 157–158) for the shock in detail.

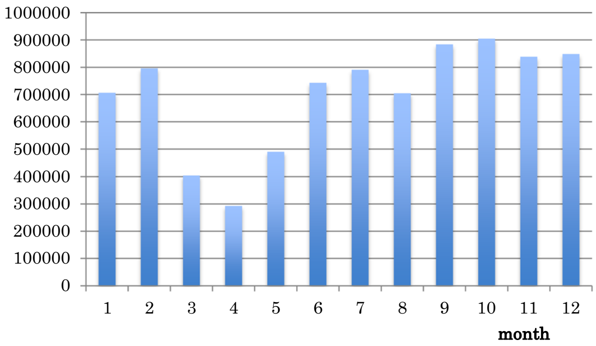

Fig. 1 Production of automobiles in Japan, 2011. (Source: Japan automobile manufacturers association, Inc.)

follows: if we spatially distribute the supply chain, the damage might be less severe on the other plants acting as backup located outside the disaster-stricken area.[4] In fact, by using the firm-level data in the affected area, Todo et al. (2013) found that having more suppliers and clients outside the affected areas mostly shortens the recovery time. Nakajima and Todo (2013) analyzed the survey conducted by Research Institute of Economy, Trade and Industry (RIETI), and showed that 8.1 % of firms that had damaged suppliers addressed the problem by finding new suppliers. The firms' client evaluation, or their satisfaction with the newly contracted suppliers, is lower than with previous suppliers combined. In terms of the quality of the newly supplied goods, however, the evaluation and satisfaction are almost the same with the previously supplied goods.

As discussed in Section 1, however, the negative reason is as follows: the firms may continually incur damage if they depend on spatially dispersed supply chains. Tokui et al. (2012) estimated that nearly 90 % of the output loss in Japan from the earthquake was due to the indirect effects of supply chain disruption. Ye and Abe (2012) and ESCAP (2013) reported in detail the spillover effects of the earthquake to other countries. Henriet et al. (2012) proposed two strategies to improve the vulnerability of the supply chain structure based on the disaggregated dynamic input-output model. The first strategy isolates many small groups of producers as far from the other groups as possible, to reduce the disaster effects. That is concentrated and clustered groups of producers are recommended. The second strategy requires producers to have as many suppliers and clients as possible to compensate for the loss incurred from natural hazards. The proposal of Henriet et al. (2012) seemed reasonable for improving the resilience of producers. Large inventories can also protect production against these hazards.[5] These policies, however, would increase production costs or compromise efficiency during normal times. Ye and Abe (2012) proposed that enterprises should consider the tradeoffs between supply chain efficiency and disaster risk preparation.

Altay and Ramirez (2010) analyzed the impact of over 3,500 natural disasters on more than 100,000 firm-year observations for a span of 15 years. They found that in the

[4] Aldrich (2012) emphasized the importance of social capital or network for dynamic resilience. Illenberger et al. (2013) analyzed the role of spatial interaction in social networks empirically.

[5] Silva and Gao (2013) and Shahabi et al. (2013) analyzed optimal location of joint inventory hubs.

case of floods, the effect is dependent on the firm's position in the supply chain, that is, upstream firms experience a more positive effect compared to downstream firms. Although classifying firms as upstream or downstream might be simplistic (i.e., all manufacturing firms are categorized as upstream, whereas retailers are categorized as downstream), such an approach presents interesting results. The results of such classification imply that in addition to the positive and negative effects of disasters on the supply chain, a conflict of interest may exist among producers of different positions, within a supply chain.

To our knowledge, no theoretical study has focused on the differences of interests among producers in a spatially dispersed supply chain with respect to static resilience. Thus, the present study makes an initial attempt to examine the issue by establishing a simple model of spatial economy.

3 The Model

3.1 Basic Settings

We set up a double-layer structure of circles where firms are categorized to capture the ideal characteristics of the supply chain over space and the cascade of spatial risks.[6] The top circle is occupied by intermediate goods producers who provide differentiated inputs for the final goods producers in the second circle.[7]

For simplicity, we focus on the supply chain of a specific final product, which can be categorized as a homogeneous good. The final goods are produced with capital and intermediate goods. To capture the basic source of fragmentation, we assume that the inputs are differentiated by the location of the intermediate goods producers; for the final goods producers, the scale economy works with respect to a variety of intermediate inputs. Thus, the final goods producers would buy inputs from most intermediate goods producers located in different places, while paying transport costs in the process.[8]

Following Ethier (1982), we adopt the technology given by

$$Y_i = A \cdot K_i^{1-\alpha} \cdot \left(\Sigma_{j=1}^{M} m_{ji}^{a} \right), \tag{1}$$

where i is the location of final goods production (i=1,$\cdots$,N),

j	is the location of intermediate goods production (j=1,$\cdots$,M),
A	is a parameter (>0)
K_i	is the capital input at location i of final goods production
m_{ji}	are the intermediate inputs from j to i, and
α	is a parameter [$\alpha \in (0,1)$].

We assume that clients pay the transport cost of their inputs (see Footnote 7); therefore, for final goods producers to use the input at their plants, they must pay the

[6] See Venables (1996) for a model of vertically linked industries in the context of the New Economic Geography, although no distances occur among firms within a supply chain in each region.

[7] This assumption of differentiated inputs comes from the example of "Renesas Shock," as described above.

[8] In the case of the Japanese automobile industry, for example, clients pay the transport cost of their inputs.

free on board (FOB) price determined by each intermediate producer, plus the transportation cost.[9] Thus, the cost of production is given by

$$C_i = r \cdot K_i + \sum_{j=1}^{M} \left(p_j + t \cdot d_{ji}^{\theta} \right) \cdot m_{ji}, \tag{2}$$

where r is the capital rent,

p_j is the FOB price of intermediate goods at j
t, θ are the parameters of transport cost (>0), and
d_{ji} is the distance between j and i.

By using the cost minimization behavior of the final goods sector, the conditional factor demand functions are given as follows[10]:

$$K_i = \left(\frac{a}{1-a} \right)^{-a} \cdot r^{-a} \cdot A^{-1} \cdot Y_i \cdot \Phi_i^{a-1}, \tag{3}$$

$$m_{ji} = \left(\frac{a}{1-a} \right)^{1-a} \cdot r^{1-a} \cdot A^{-1} \cdot Y_i \cdot \varphi_{ji}^{\frac{1}{1-a}} \cdot \Phi_i^{a-2}, \tag{4}$$

where $\varphi_{ji} = p_j + t \cdot d_{ji}^{\theta}$ and

$$\Phi_i = \sum_{j=1}^{M} \varphi_{ji}^{-\frac{\alpha}{1-\alpha}}.$$

Next, the production technology of intermediate goods is assumed as

$$y_j = B \cdot L_j, \tag{5}$$

where B is a parameter (>0) and

L_J is the labor input at j.

The production cost is given by

$$c_j = w \cdot L_j + F, \tag{6}$$

where w is the wage rate and

F is the fixed cost for a variety.

We consider only the supply chain in this study. Thus, we assume a small open economy with respect to basic production factors: capital and labor. The prices of these factors (e.g., capital rent and wage rate) are given exogenously. We assume Eq. (6) in this study because it is common to introduce a fixed cost for the production of a variety in monopolistic competition models. The fixed cost of a variety is often used to investigate the number of firms sustained in the equilibrium of standard monopolistic competition models. Therefore, a lower fixed cost corresponds to a larger equilibrium number for intermediate goods producers, and vice versa. In this study, however, the number of firms is given exogenously in each numerical simulation to compare the static resilience at different levels of locational dispersion; consequently, the fixed cost

[9] Free on board (FOB) price is the price effective for the trade at the plant only, and does not include the transport cost. FOB price is also referred to as the mill price.
[10] For the readers who are not familiar with microeconomics, please refer to some textbooks (e.g., Silberberg 2000).

does not work explicitly hereafter. Therefore, given Eq. (4) as the demand from the final goods producers, the profit of the intermediate sector used in the simulations is not the net of the fixed costs as follows:

$$\pi_j = \eta \cdot \left(p_j - \frac{w}{B}\right) \cdot \sum_{i=1}^{N} Y_i \cdot \varphi_{ji}^{\frac{-1}{1-\alpha}} \cdot \Phi_i^{\alpha-2}, \tag{7}$$

where $\eta = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha} \cdot r^{1-\alpha} \cdot A^{-1}$.

Although Φ_i includes φ_{ji} as a factor, we assume that each intermediate goods producer would suppose Φ_i as a constant. The producer then tries to maximize the profit by choosing P_j.

3.2 Symmetric and Asymmetric Cases

First, we examine the symmetric cases in Fig. 2. In these cases, the final goods producers are located in the same points as the intermediate goods producers; no specific affiliation exists, however, among the producers in the same location.

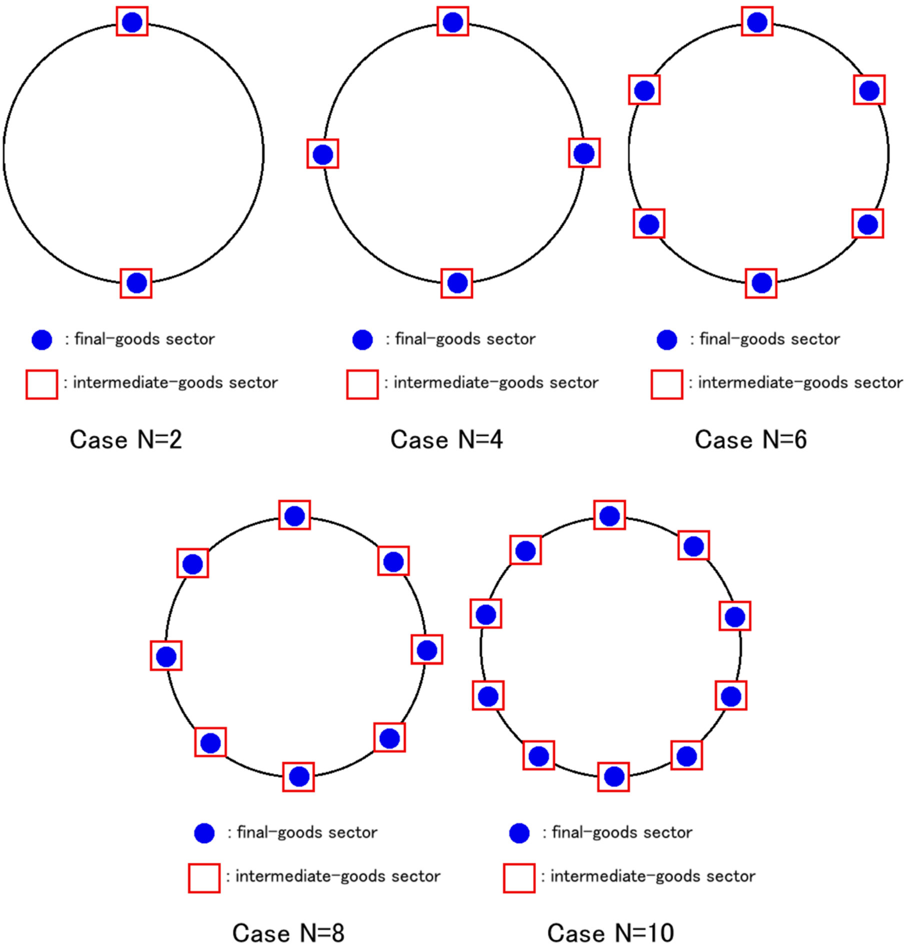

Fig. 2 Symmetric cases (M = N)

Second, we set the "asymmetric" cases in Fig. 3 specifically to examine the effects of the dispersion of the final goods sector. In these cases, we fix the location of the intermediate goods producers as M=8 and vary the number of the location of the final goods producers as N=1, 2, 4, 8.

In either case, the intermediate inputs are assumed to be transported along the shorter circumference. We do not, however, consider the damage on the transportation from the spatial risks in this instance.

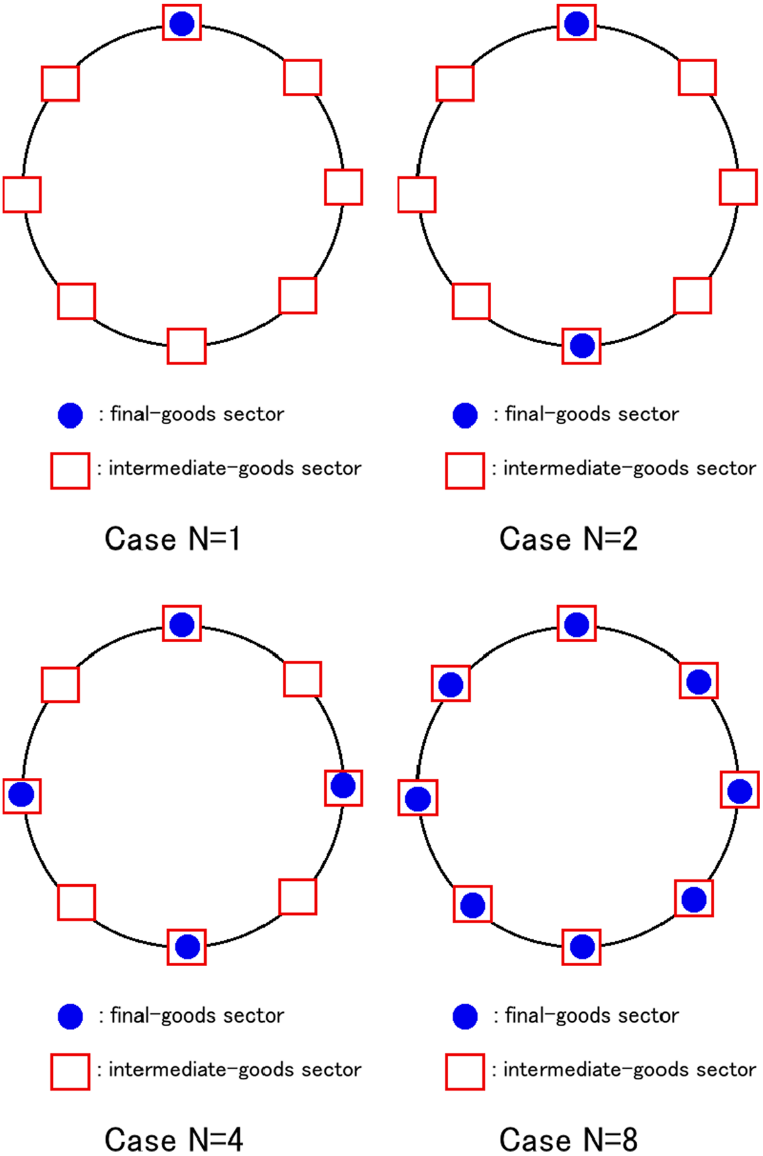

Fig. 3 Asymmetric cases (M=8: fixed)

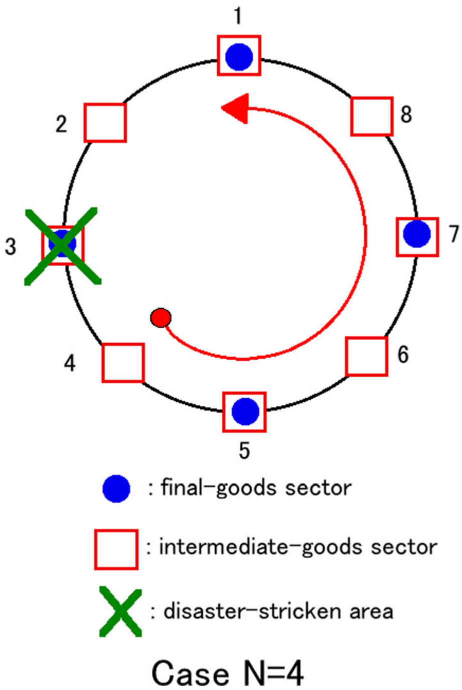

Fig. 4 Asymmetric cases with transportation damage (Example of case N=4 and location #3 is stricken)

3.3 Asymmetric Cases with Damage on Transportation

In this subsection, we assume that the hazards also damage the transportation in the supply chain. On the basis of the asymmetric cases in Fig. 3, the transportation link is assumed to be disrupted at the same point as the stricken plant. For example, in Fig. 4, the plants and transportation link at number 3 are stricken. Thus, the final goods producer at number 1 has to make a detour in transporting the intermediate goods produced at number 4. In this case, the distance increases 1.67 times than normal.[11]

4 Simulation Results

4.1 Basic Simulation Procedure

In the numerical simulations described below, we first examine the cases without spatial risks as the basic cases. To examine the performance of this small open economy, we further assume that the total output of the final goods in each of these cases is a fixed constant. Each final goods producer shares the same amount of output. Likewise, the price of the final goods P_i is determined so that the profit of the final goods sector Π_i is zero in the basic cases.

[11] See Yamada et al. (1992) or Omer (2013) for studies about restoring the damaged transportation network. Cats and Jenelius (2014) formalized the value of real-time information provision for reducing disruption impacts. Yaghini et al. (2014) used capacity consumption analysis for under construction railway routes.

Table 1 Setting of parameters

$\sum_i Y_i$	1
α	0.75
A	1
B	1
θ	1
t	1
r	0.03
w	1
circumference	1

We then introduce a spatial hazard, such as an earthquake, to the setting. To simplify the analysis, we assume that an earthquake only strikes a location and all locations have the same probability of being stricken, and we do not consider the cases where several locations are stricken simultaneously.

In this paper, we focus on the short-term damage of the spatial hazard. Thus, both prices P_i and p_j are fixed as before the disaster.[12] Although either sector cannot produce goods in the stricken location, the final goods producers in other locations can change their procurement pattern of intermediate goods to maintain the level of output as before, indicating that under these conditions, the final goods producers minimize their cost by selecting the size of procurement for each type of intermediate goods from an undamaged location. Even in the short term, these measures taken by the private sector in this case may contribute to static resilience.

Consider the case in which each location produces the same amount of output (i.e., equal share of the fixed total amount) independently. In the short term, if the number of producing locations doubles, the expected damage to each location becomes half in terms of the output, whereas the probability of being stricken doubles. Therefore, assuming risk neutrality defined by von Neumann and Morgenstern (1953), the "null hypothesis" in this case may mean that "the degree of dispersion does not matter against the risk, because a greater dispersion corresponds to lesser damage at a location yet greater probability of being struck.[13] " For example, if the probability of an earthquake striking a location is the same for all points in the circle (i.e., here, a uniform distribution is assumed for the probability of being struck by hazards over the circle), and if we do not consider the possibility of other plants acting as backup in locations outside the affected area, then the expected instantaneous loss should be irrelevant to the distribution of economic activities (total output is fixed here) in the circle.

Given that the present paper is an initial attempt to examine such hypothesis based on the spatially dispersed supply chain, and the study will not reproduce some specific

[12] Henriet et al. (2012) adopted similar assumptions. Hallegatte and Przyluski (2010) proposed a definition of the economic cost of a disaster for longer periods.

[13] In traditional economic theory, risk itself is given exogenously, and agents should decide whether to take it or not, which is different from the definition of risk given by Wisner et al. (2004) in Footnote 1.

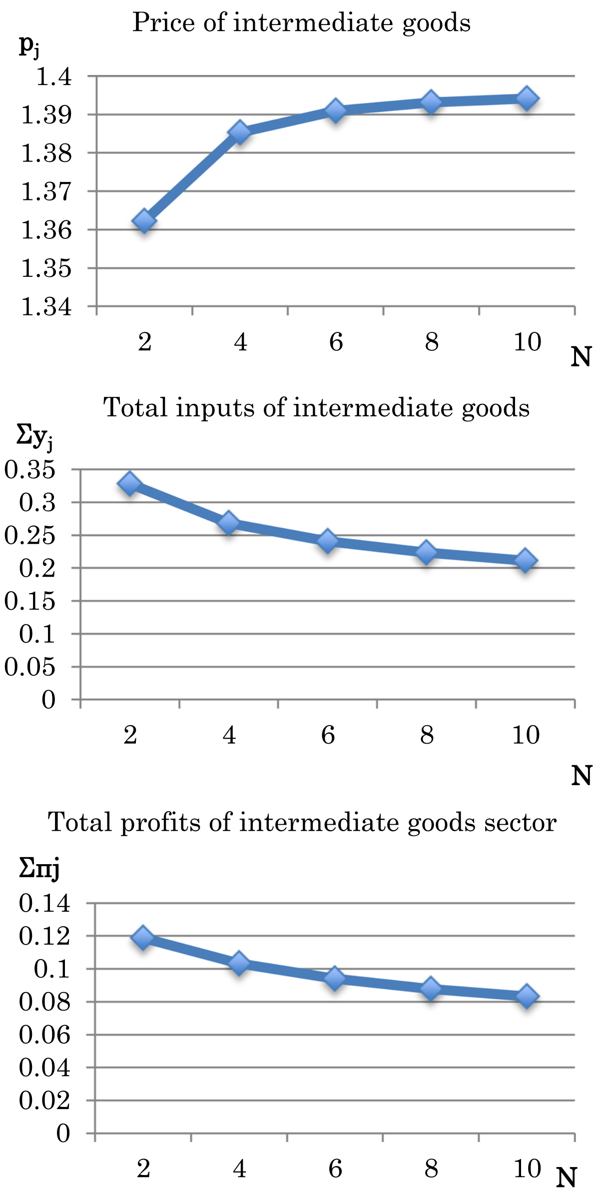

Fig. 5 Symmetric cases: basic cases of intermediate goods

real events through proper calibration, the numerical simulations described below use simple parameters, as shown in Table 1. We adopt relatively realistic values for the capital rent r and the technological parameter α, and the other parameters are set to prevent any loss of generality.[14]

[14] Although changing the parameter values is interesting as comparative statics or sensitivity analysis, we could extract the essential characteristics of the supply chain by using this setting at this stage.

4.2 Symmetric Cases

First, we examine the symmetric and basic cases. The results are shown in Figs. 5 and 6. Figure 5 shows the intermediate goods sector, whereas Fig. 6 presents the final goods sector. Basing on these figures, we make the following observations:

Observation 1

- If N (=M) increases, the markup or price of the intermediate goods p_j, also increases because of the dispersion of the final goods production.
- If N (=M) increases, the efficiency of the final goods production also increases because of the increase in the variety of intermediate goods.

We adopt the FOB pricing policy for intermediate goods producers (i.e., final goods producers pay the transport costs). Therefore, the markup of the goods increases when the final goods producers disperse over the circumference. As variety increases, however, the final goods production becomes more efficient, and it is able to save the intermediate goods $\sum y_j$ and the capital inputs $\sum K_i$ for a fixed level of output. In the economy, the total output of final goods is fixed, and the profit of the sector is zero. In addition, the factor markets of

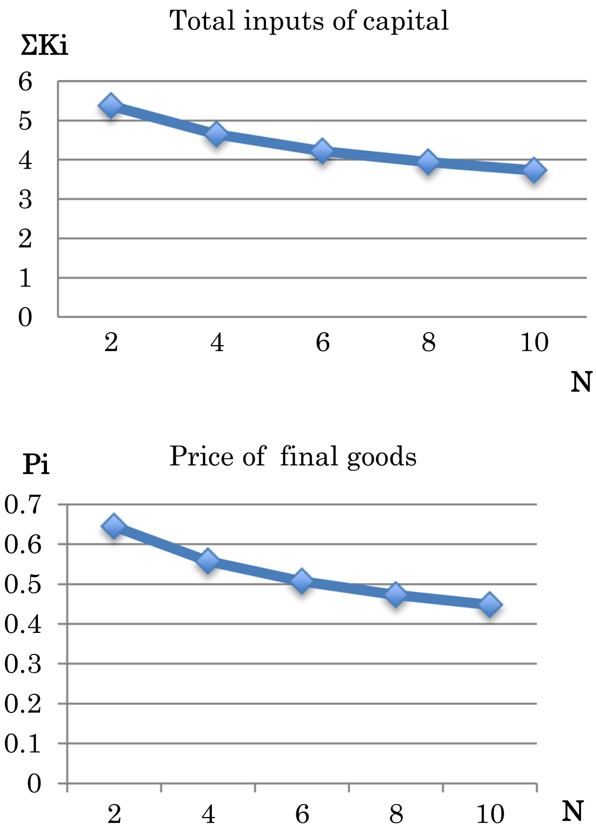

Fig. 6 Symmetric cases: basic cases of final goods

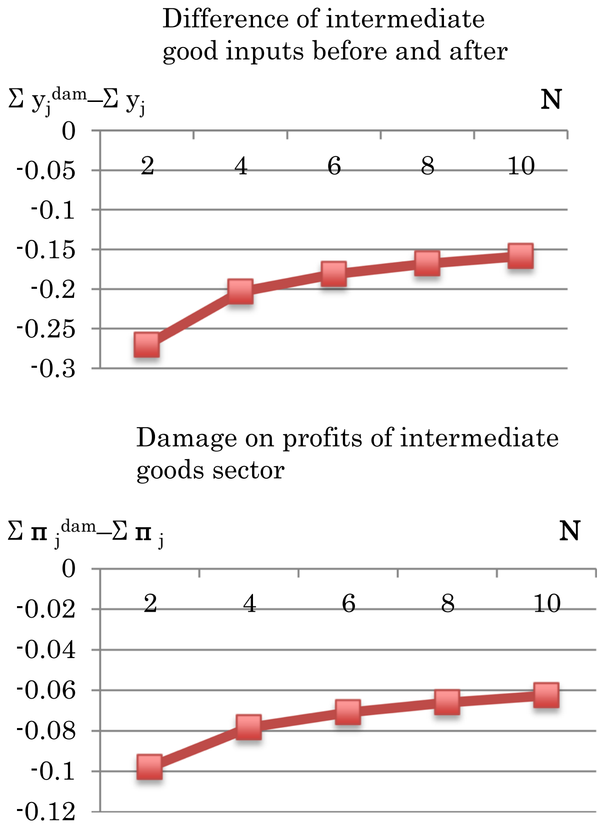

Fig. 7 Symmetric cases with damage on intermediate goods

capital and labor are perfectly open and competitive. Therefore, the performance of the economy could be captured by the excess profits of intermediate goods $\sum\pi_j$ and the price of final goods P_i. Nevertheless, once we explicitly introduce the fixed cost for a variety to the numerical simulations in Eq. (6), the excess profits would be absorbed for the fixed cost, through the free entry and free exit conditions in a standard monopolistic competition. Thus, the price of final goods is solely appropriate as the measure of economic performance in this case. If no spatial risk exists (i.e., in normal time), the dispersion/fragmentation of production is good for the economy because of the increase in variety.

We now introduce the spatial risk to the setting by following the procedure described above. The results are shown in Figs. 7 and 8 where the damage is measured by the differences of the results from the normal time (superior "dam" means the values at damage or disaster in the figures hereafter).[15] Basing on these figures, our observations are as follows:

Observation 2 • If N (=M) increases, the total expected damage of the disaster to the intermediate goods sector measured by the excess profits $\sum\pi_j$, would decrease.

[15] In Figs. 8, 12 and 14, note that the profit of final goods sector in normal times is zero by assumption (i.e., $\sum\Pi_i$=0).

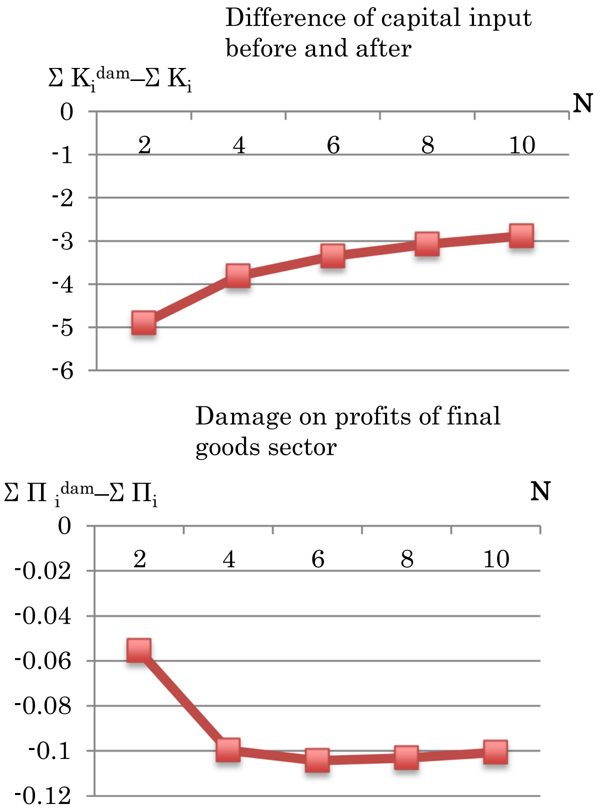

Fig. 8 Symmetric cases with the damage on final goods

- If N (=M) increases, the total expected damage of the disaster to the final goods sector measured by the profits $\sum \Pi_i$, would not decrease.

In order to maintain the same level of output for the final goods sector outside the affected area, a greater demand for both intermediate goods $\sum y_j$ and capital inputs $\sum K_i$ is needed based on the increase in locations N.

Despite the spatial risks, dispersion/fragmentation is beneficial to the intermediate goods sector, which is relatively resilient enough to withstand the risks. To an extent, this is opposite for the final goods sector. Thus, there may be some conflict of interest between the final goods and intermediate goods sectors in terms of the progress of dispersion/ fragmentation over space. In the symmetric cases, however, the dispersion of the intermediate goods sector is better for the final goods sector because of an increase in variety, as shown in Observation 1. Therefore, in the following subsection, we remove this effect to focus on the static resilience of the final goods sector with respect to its own dispersion.

4.3 Asymmetric Cases (Without Damage on Transportation)

We examine the asymmetric cases described in Section 3.2 to further investigate the possible conflict of interest between the final goods and intermediate goods sectors. We obtain the results for the basic cases by fixing the location of the intermediate goods producers and varying the number of locations of the final goods producers. The results of the investigation for the intermediate goods sector and the final goods sector are shown in Figs. 9 and 10, respectively. Basing on these figures, we make the following observations:

Observation 3 • If N increases, the markup or price of the intermediate goods p_j (in terms of weighted average according to the quantity

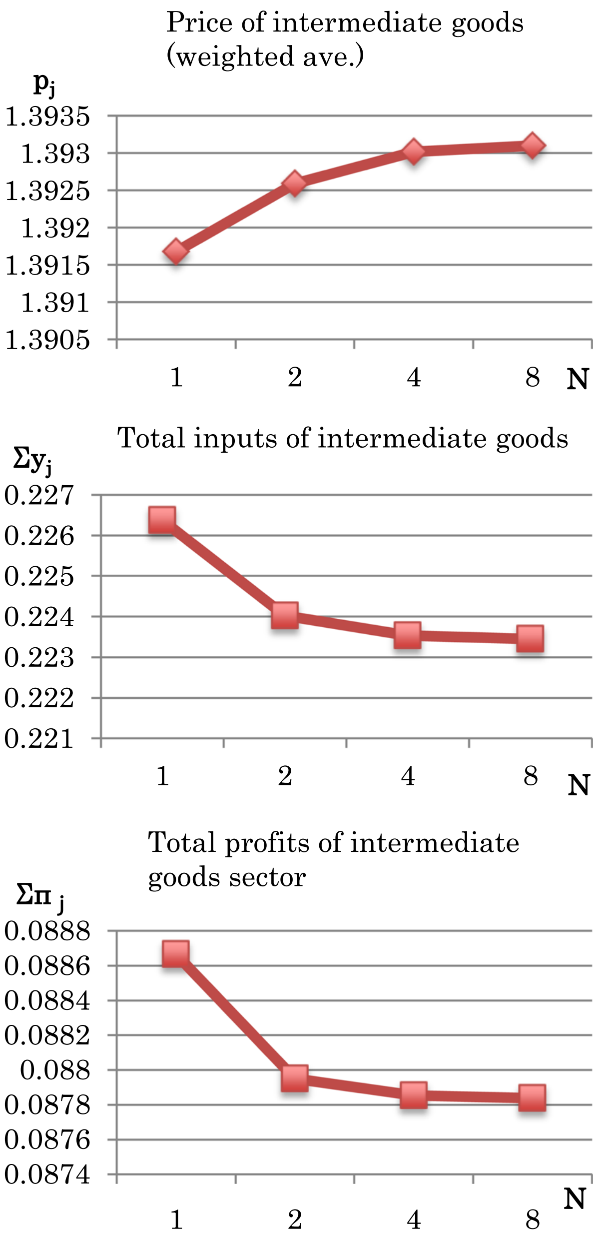

Fig. 9 Asymmetric cases: basic cases of intermediate goods

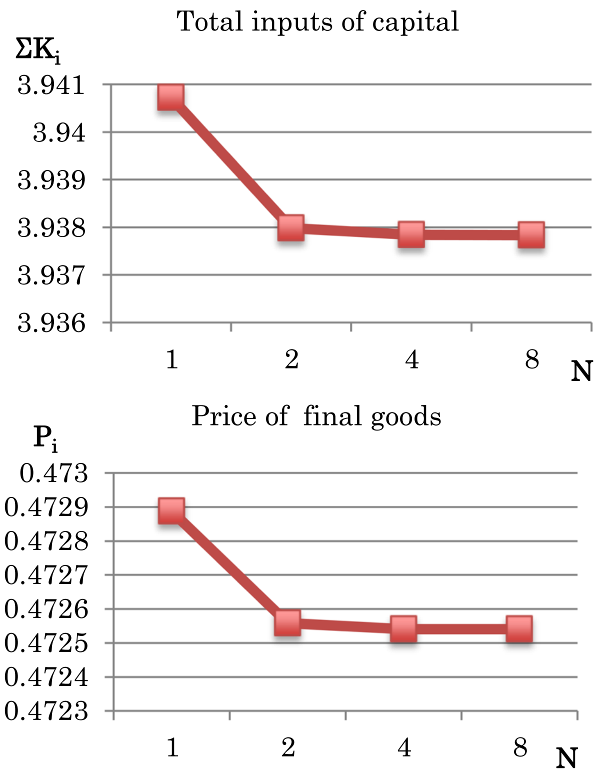

Fig. 10 Asymmetric cases: basic cases of final goods

produced) also increases because of the dispersion of the final goods production.

- If N increases, the efficiency of the final goods production also increases because of the dispersion; thus, the price of the final goods decreases.

In cases where the location of the intermediate goods producers is fixed, we can expect a positive outcome when the final goods producers further disperse independently because of the increase in the accessibility to the intermediate goods. Again, the final goods producers are able to save the intermediate goods $\sum y_j$ and the capital inputs $\sum K_i$ for a fixed level of output.

We then introduce the spatial risk to this asymmetric setting. The results are shown in Figs. 11 and 12. Basing on these figures, our observations are as follows:

Observation 4

- If N increases, the total expected damage of disasters to the intermediate goods sector, measured by excess profits $\sum \pi_j$, would decrease. In particular, the resilience of the intermediate goods sector has greatly improved from N=1 to N=2.
- If N increases, the total expected damage of disasters to the final goods sector, measured by profits $\sum \Pi_i$, would also increase.

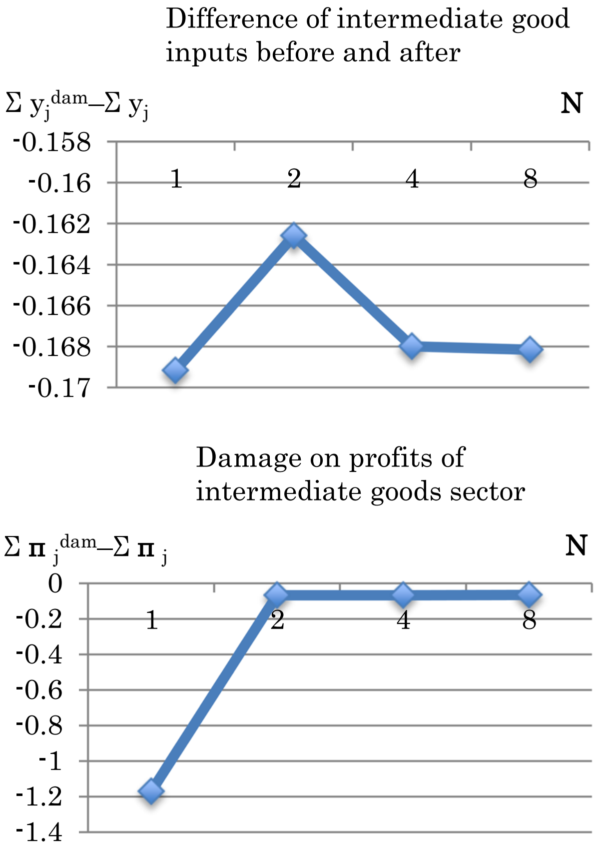

Fig. 11 Asymmetric cases with the damage on intermediate goods

In the case of asymmetric distributions, the trade-off between the interests of the final goods and intermediate goods sectors becomes clearer. From the viewpoint of the intermediate goods sector, a dispersed final goods sector is desirable. By contrast, in terms of static resilience, being spatially concentrated is better for the final goods sector. These results are consistent with the empirical findings of Altay and Ramirez (2010) who posited that upstream firms experience a more positive effect from natural disasters, and downstream firms experience the opposite. In this case, the movement of the intermediate goods supply $\sum y_j$ looks irregular if $N=2$, whereas there is more demand for capital inputs $\sum K_i$ based on the increase in locations N.

4.4 Asymmetric Cases (With Damage on Transportation)

As described in Section 3.3, we assume in this subsection that the hazards also damage the transportation in the supply chain. On the basis of the asymmetric cases in Fig. 3, the transportation link is assumed to be disrupted at the same point of the stricken plant. The results are shown in Figs. 13 and 14, where we

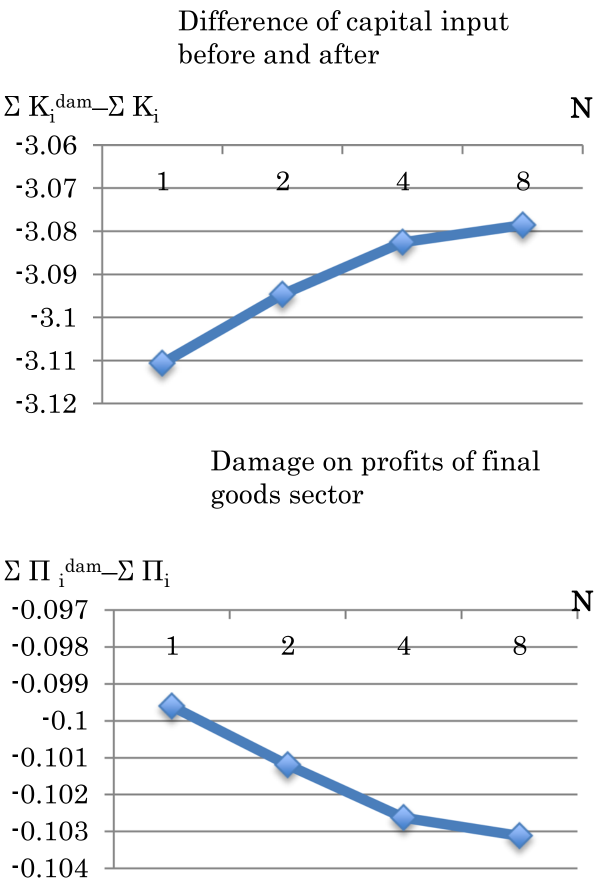

Fig. 12 Asymmetric cases with the damage on final goods

compare the outcome of this case with the results presented in the former subsection (i.e., Figs. 11 and 12). Basing on these figures, our observations are as follows:

Observation 5

- With the damage on transportation, the total expected damage of disasters to the intermediate goods sector, measured by excess profits $\sum \pi_j$, would not increase significantly.
- With the damage on transportation, the total expected damage of disasters to the final goods sector, measured by profits $\sum \Pi_i$, would increase significantly.

To be precise, the disruption of the transportation network has greater effect on the final goods producers than on the intermediate goods producers. This result again supports the empirical findings of Altay and Ramirez (2010). Both intermediate goods $\sum y_j$ and capital inputs $\sum K_i$ are demanded more in this case, according to the damage of transportation.

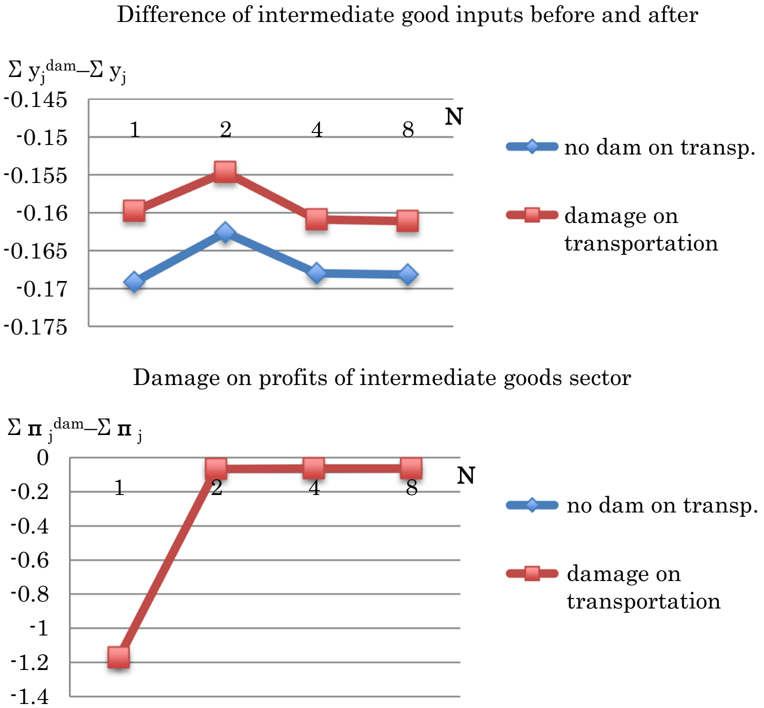

Fig. 13 Asymmetric cases with missing link (The damage on intermediate goods producers)

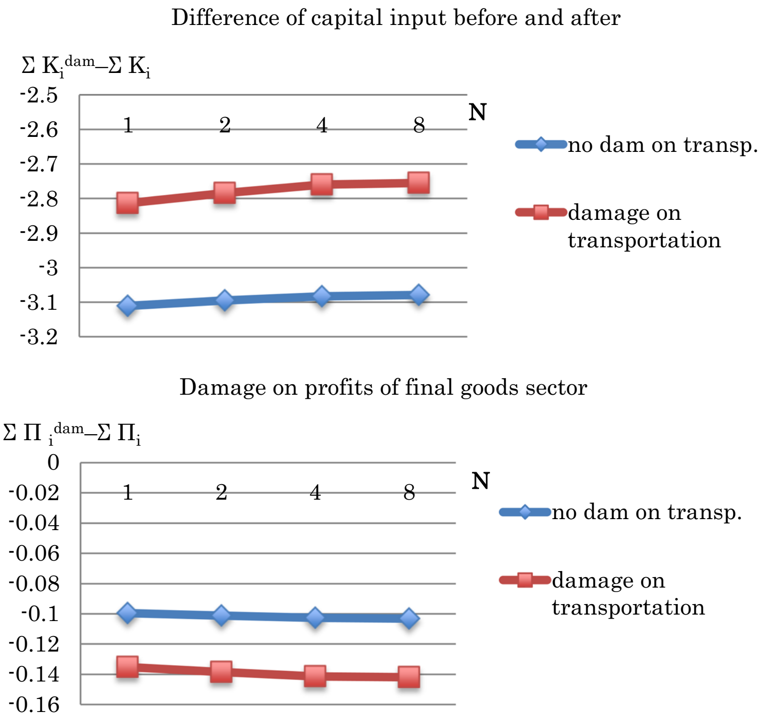

Fig. 14 Asymmetric cases with missing link (The damage on final goods producers)

5 Conclusion

By establishing a simple model of a spatially dispersed supply chain, we examined the static resilience of the structure with respect to the degree of dispersion, the possible damage on transportation, and the position of producers in the supply chain (i.e., upstream or downstream). Our main results are discussed in the succeeding paragraphs.

In normal time, or when there are no locational hazards, and given the technology with increasing returns to scale and variety, spatial or geographical dispersion of producers is always beneficial. This result is consistent with the recent phenomenon of the rapid fragmentation of foreign and domestic trade proceeds. We are faced, however, with natural and man-made hazards such as earthquakes, floods, hurricanes, and political conflicts almost everywhere. The effects of these hazards often disrupt some parts of a supply chain, and such damage is diffused over space. By focusing on static or instantaneous resilience, we find that on the one hand, dispersion/fragmentation is beneficial for the intermediate goods sector, which is resilient enough to withstand the risks. On the other hand, however, the effect of dispersion/fragmentation on the final goods sector is the opposite because this sector is less resilient to withstand the risks. This result is consistent with the empirical findings of Altay and Ramirez (2010) who stated that upstream firms experience a more positive impact from disasters, and downstream firms experience the opposite. In addition, when the transportation system in the supply chain is also damaged, the damage would be more significant for the final goods sector than for the intermediate goods sector. Overall, in terms of static resilience, the results of this study imply the existence of a conflict among the sectors that comprise a supply chain.

Although the results of the numerical simulations seem interesting, and the essential characteristics of a stratified supply chain were captured, the analysis is still a prototype of the theoretical experiment for the investigation. First, our analysis concerns static resilience only. There is still need to analyze dynamic resilience, which should be more important for the economy in general. Given that most empirical studies (some of them are introduced in Section 1 and Section 2) are describing the behavior of communities, firms, and governments after disasters, developing theoretical models to examine or reproduce the findings of these studies would be necessary.

Lastly, worldwide transportation network is changing drastically, whereby the supply chain is also affected faster than before.[16] To improve the dynamic resilience of transportation networks, a new study on the strategic restoration of transportation networks should be performed. We examined, however, the simplest network (i.e., a circle) in the current study, without the possible restoration of a transportation network.

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[16] Caschili et al. (2014) studied how shipping companies integrate and coordinate their activities and investigated the topology and hierarchical structure of inter-carrier relationships.

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