Propagation of Shocks due to Natural Disasters through Global Supply Chains*

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Abstract

In this paper, we take Hurricane Sandy that hit the east coast of the United States in 2012 as a source of exogenous negative shocks and examine its indirect effects on the global economy through supply chains. More specifically, using firm-level data on global supply chains, we examine how sales growth of firms in and outside the US changes when their direct and indirect suppliers or customers are damaged by the hurricane. Our results show that in most cases the negative effect on customers outside the US is similar in size to the effect on firms in the US, concluding that negative shocks due to the hurricane propagated to downstream customers through global supply chains. However, the effect on suppliers, or upstream propagation, is different; the negative shock propagated to suppliers in the US but not beyond the US border. We further find that the negative effect is heterogeneous in size across firms depending on the presence of other types of inter-firm links in addition to supply chain links. For example, the negative effect is smaller when the supply chain link is associated with a shareholding link, whereas it is larger when associated with a research collaboration link. In addition, the structure of each firm's ego-network also influences the level of propagations.

Keywords: global supply chains, propagation, disasters.
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1. Introduction

Recent studies find that negative shocks may propagate through input-output linkages to both upstream and downstream firms, leading to substantial damages in the whole economy (Acemoglu et al., 2012; Caliendo et al., 2014; Di Giovanni and Levchenko, 2010). Although these studies rely on input-output tables at the sectoral level, more recent studies utilize firm-level data with information on supply chain links to investigate this issue (Barrot and Sauvagnat, 2016; Carvalho et al., 2014; Lu et al., 2017). They find that negative shocks due to natural disasters affect production and financial performance of firms that are directly or indirectly connected with firms damaged directly by the disasters.

One shortcoming of these existing studies is that they focus on input-output linkages or supply chains within a country such as the United States and Japan but do not incorporate propagation across countries due to data limitation. However, because supply chains, production networks, and value chains have recently expanded rapidly beyond national borders (Baldwin, 2016), negative shocks may propagate across countries through such networks. The study by Boehm et al. (2015) is an exception, in that they examine propagation from parent firms damaged by a disaster to their overseas affiliates. However, propagation between unaffiliated firms is not explored in their study.

To fill the gap, this study utilizes a large firm-level dataset of major firms around the globe that contains detailed information on their supply chain ties to investigate how negative shocks due to natural disasters propagate across countries through the global supply chains. More specifically, we take Hurricane Sandy as a source of negative shocks and examine how sales of firms change when their direct and indirect customers or suppliers are located in areas affected by the hurricane. The Hurricane Sandy hit the east coast of the United States in 2012 and caused an economic loss of 50 billion US dollars, the second largest economic loss in the world since 2010 (EM-DAT, 2017). The dataset covers 58 thousand major firms in the world, including 10,000 in the United States, 3,400 in Japan, and 2,200 in the United Kingdom. In addition, we merge the dataset on the global supply chains with another large firm-level dataset that contains information on shareholding and patent co-application ties to examine how multi-level networks of firms amplify or lessen propagation of negative shocks through supply chains.

Our findings can be summarized as follows. First, we find that the growth rate of sales of customers and suppliers of directly damaged firms after the hurricane was significantly lower than other firms if the customers and suppliers are located in the United States. However, the similar negative impact is observed only for customers outside US and suppliers outside the US are not affected. This finding confirms intra- and international transmission of negative shocks downstream through the global supply chains. Second, the sales growth of customers of customers of directly damaged firms (or, customers within two steps of supply chains) was also negatively affected. Moreover, the negative effect of supply chain ties with damaged firms on sales growth varies depending on measures of firm networks, such as the local clustering coefficient that indicates the density of ego networks. Finally, the negative effect of supply chain ties with directly damaged firms is alleviated when supply chain ties are associated with shareholding ties, while it is enhanced when supply chain ties are associated with research collaboration. This finding may indicate that importance of considering other types of relations that supply links are embedded in.

This study contributes to the literature in the following three ways. First, although some existing studies focus on either supply chains within a country or between parent firms and their overseas affiliates, as mentioned earlier, the present paper incorporates most major inter-firm transaction relations in the world including international and arm's-length relations. Second, as our data include the global network of major firms, we can investigate how the network structure of each firm, measured by local clustering coefficient, contributes to shock propagation from natural disasters. Finally, we look into interactions between supply chains and other types of inter-firm networks, such as shareholding networks to see whether other types of links strengthen or alleviate negative effects through supply chains.

2. Empirical Strategy

2.1. Conceptual framework

When a natural disaster such as a hurricane or an earthquake hits firms' production plants, their production activities may be fully or partly disrupted due to destructions of physical capital (e.g., machinery and buildings) and lack of supply of water, gas, or electricity. When these directly damaged firms are suppliers of parts and components to other firms, the disaster may indirectly affect customers of the directly damaged firms because the customers lack the supply of parts and components. Furthermore, because supply chains are multi-layered from final assemblers to the most upstream suppliers, the customers of directly damaged firms may be suppliers of some other firms. If this is the case, the negative shock due to the disaster may propagate to more downstream customers through supply chains. The propagation in the opposite direction, i.e., upstream propagation from customers to suppliers, can also be the case due to lack of demand from damaged customers. Therefore, our benchmark hypotheses are as follows.

Hypothesis 1: The sales growth of customers and suppliers of firms damaged directly by a natural disaster is lower than otherwise due to supply chain disruptions.

Hypothesis 2: The sales growth of customers of customers (hereafter we call them "2-step customers") and suppliers of suppliers (2-step suppliers) of firms damaged directly by a natural disaster is lower than otherwise due to supply chain disruptions.

In addition, because we will utilize data for firms in the world and global supply chains, we can distinguish between effects on customers (suppliers) in the United States, i.e., downward (upward) propagation within the country, and effects on customers (suppliers) outside the US, i.e., downward (upward) propagation across countries. However, it is not clear whether propagation effects within or beyond the country is larger. On one hand, damaged firms in the US, which are under limited operations, may give higher priority to US domestic firms[d]. Therefore, firms outside the US may find it more difficult to get (sell) goods. On the other hand, the longer time to take before the goods are delivered beyond a country may buy firms outside the US more time to get impacts from the damaged firms, so they can find alternative transaction partners while consuming goods delivered before the disaster. The difference of search cost may also affect the level of propagation of negative shocks. The disaster shock degrades US economy, but non-US economies, in general, are not affected instantly. Assuming that searching new transaction partners within a country costs less, firms outside the US can substitute their local firms for the damaged US firms more easily. This presumption leads to the following hypothesis.

Hypothesis 3: The negative effect of damaged suppliers (customers) in the United States on customers (suppliers) in the United States may be larger or smaller than that on customers (suppliers) outside the US, depending on the priority and the search cost.

Finally, we consider the difference of the level of propagation of disaster shocks through supply chains depending on the direction of propagations. Carvalho et al. (2014) finds that firms with damaged customers are more likely to find new transaction partners than those with damaged suppliers. Since substitutions are the major way to deal with the propagation of negative shocks, we obtain the last hypothesis.

Hypothesis 4: The negative effect of damaged suppliers on their customers is larger than that of damaged customers on their suppliers.

2.2. Estimation equation

To test these hypotheses above, we consider the following estimation equation:

$$\Delta Sales_{i(2011-t)} = \beta_0 + \beta_1 Shock_{i2011} + \beta_2 X_{i2011} + \varepsilon_{it} \, . \quad (1)$$

The dependent variable, $\Delta Sales_{i(t\text{-}2011)}$, is the growth rate of sales of firm i from 2011 to year t where t is either 2012 or 2013. We experiment with two cases because the Hurricane Sandy hit the US in October 2012. Thus, immediate propagation is captured by sales growth from 2011 to 2012, whereas growth from 2011 to 2013 can capture longer-run propagation.

Shock is the vector of key independent variables in terms of supply chain ties with suppliers and customers directly hit by the Hurricane Sandy. We measure supply chain ties with directly damaged suppliers in two ways: the log of the number of such suppliers plus one and a dummy variable which takes a value of one if the number of such suppliers is one or more. When we use the former measure, we assume that the negative effect of damaged suppliers increases as the number of damaged suppliers rises. However, the negative effect may not monotonically increase in the number of damaged suppliers because the lack of only

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[d] Mizuho research institute (2011) summarizes the concerns of the propagation of negative shocks due to Great East Japan Earthquake to Asian countries. They report that there are concerns about both demand shock and supply shock, including the mention of the effect coming from priority difference.

one part or component leads to the complete halt of production lines. This is particularly the case when input substitution is quite difficult. To incorporate this possibility, we also use the dummy variable for the link with damaged suppliers. In addition to firm *i*'s direct suppliers directly hit by the hurricane, *Partner* includes measures of suppliers of firm *i*'s suppliers, or firm *i*'s indirect suppliers with two steps. In this case, we also use the number of two-step suppliers or their dummy. To further distinguish between the propagation within the US and from the US to other countries, we include the interaction term between those variables and dummy indicating whether firm *i* is in the US or not.

By contrast, when we examine upstream propagation, focusing on supply chain ties with customers directly damaged by the hurricane, we rely on the number of such customers or two-step customers, rather than dummies for the presence of these customers. This is because propagation of negative shocks to upstream firms is caused by reductions in demand by damaged customers. In other words, the negative effect of one damaged customers should be different in size from that of two or more damaged customers.

The vector of the control variables *X* includes firm attributes such as sales growth from 2006 to 2011, the number of workers in logs, the value of total assets in logs, sales per worker in logs, firm age, industry dummies, and country dummies. It also includes four measures of the structure of the supply chain network, as described later in detail.

2.3. Estimation method

To estimate equation (1), we use ordinary least squares (OLS) regression. This simple method is appropriate in the present case because the Hurricane Sandy is an exogenous shock and therefore whether a firm is linked to a damaged firm should be exogenously determined (after controlling for the total number of links the firm has). We check the exogeneity of the shock by testing the correlation between the shock and pre-disaster sales growth.

3. Data

3.1. Data sources

This study uses three datasets, LiveData of FactSet Revere and Osiris and Orbis of Bureau van Dijk (BvD). We merge information from these three datasets because no existing firm-level dataset includes data on global supply chains, shareholder and research collaboration ties, together with financial performance all in one. LiveData includes information on supply chain relations collected from public sources such as financial reports and web sites. Although FactSet Revere originally focused on US firms, it recently expanded its coverage to other regions, including Europe and Asia. We utilize LiveData for 2011, one year before the Hurricane Sandy, to identify pre-disaster global supply chains that include 110,313 firms and 66,553 supply chain ties. Among the 110,313 firms, 17,656 are located in the US, 3,908 in Japan, 2,499 in the United Kingdom, 1,378 in Germany, and 2,947 in China.

The other datasets, Osiris and Orbis, is an integration of firm-level data from a number of countries. Orbis covers 200 million firms around the world including non-listed small and medium enterprises, while Osiris is a subset of Orbis that mostly covers publicly listed firms. Because Osiris contains detailed financial information, we extract each firm's information about sales, the value of total assets, the number of employees, and firm age from Osiris. Orbis contains information about shareholding and patent-application relations between firms. Thus, we can identify shareholding and patent-application networks of firms in the world. Because patents are applied mostly by co-inventors, we utilize the patent-application network as a proxy for the research collaboration network. In Orbis, the number of shareholding ties in 2011 is 6,179,501, whereas the number of firms with any shareholding tie is 6,964,796. Among them, 1,994,713 are located in the United States, 378,671 in Japan, 524,926 in Germany, 361,150 in the United Kingdom, and 34,405 in China. Our data on patents are based on patents approved by any patent office in the world. However, it takes time for applied patents to be approved, we focus on currently applied patents before the day Hurricane Sandy hit the United States. The total number of such patent application ties is 834,706 for 641,862 patents. The number of firms that have any patent application tie with other firms is 63,442: 15,167 are located in the US, 6,121 in Japan, and 621 in China.

We merge LiveData, Osiris, and Orbis using the International Securities Identification Number (ISIN). Because ISINs are usually provided to publicly listed firms, we cannot merge most of the non-listed firms in LiveData. Besides, we restrict our sample to firms which are not directly hit by Hurricane Sandy[e] and have at least one transaction partner. We also face firm age restriction and number of ties restriction during the variable construction process. Accordingly, the total number of observations for our benchmark regression is 2,685, among which 1,387 are in the US, 110 in Japan, 145 in the UK, 82 in Germany, and 282 in China (Table 1).

3.2. *Variable construction*

Our key variables related to supply chains are constructed using the full information of the global supply chains in 2011, one year before the Hurricane Sandy, identified in the LiveData of FactSet Revere, which are visualized in Figure 1. In other words, although the sample for our regression analysis is a sub-sample of firms in the LiveData that can be merged with the Osiris and Orbis data using ISIN, we compute measures of the global production network using all firms in the LiveData including firms dropped from the sample for the regressions. Below, we explain how to construct measures of suppliers for the brevity of presentation, but we also construct measures of customers in the same way. Accordingly, we compute the number of suppliers and 2-step suppliers of each firm. To identify direct and indirect links with suppliers directly damaged by the Hurricane Sandy, we also compute the number of each firm's suppliers in the areas damaged by the hurricane and 2-step suppliers in the damaged areas. The areas damaged by the Hurricane Sandy are identified by the area coded as very highly damaged areas in FEMA Hurricane Sandy Impact Analysis FINAL (Security, 2017). Further, we distinguish between each firm's suppliers and 2-step suppliers in the same country (hereafter, domestic suppliers) and those in other countries (foreign suppliers). To examine possible differences between the propagation of negative shocks within the country and across countries, we

[e] We drop if firms are located in highly or very highly impacted area based on FEMA definitions.

incorporate into regressions the interaction term between a variable representing links with damaged suppliers and the dummy variable for non-US firms. In the regressions, we will use either the log of the number of the various types of suppliers plus one or the dummy variable for the presence of any such type of supplier.

In addition, we utilize four measures to represent characteristics of each firm's position in the global supply chains. The first two, the degree and PageRank, measures the centrality of each firm (or node in the terminology of network science). The degree is the number of links of each firm with others. A disadvantage of this measure is that it ignores the centrality of the firm's partners. The degree of a firm linked with k firms that are linked with many others and the degree of a firm linked with k firms that have no other partners are both k. To incorporate the centrality of a particular node's partners (or neighbors) into the centrality of the node, the largest eigenvector of the adjacent matrix of the network is often used as a centrality measure. However, this eigenvector centrality measure is not appropriate to a network which can be divided into several sub-networks without any link to each other because in that case, the eigenvector centrality is 0 for any node in sub-networks except for those in the largest sub-network. In addition, the eigenvector may not be uniquely determined for directed networks, such as supply chain and shareholding networks. To overcome these problems, Page et al. (1999) developed an extended eigenvector centrality measure, PageRank, that is often used to evaluate the centrality of web sites on the Internet.

Another network measure is Burt’s constraint. Burt (1992, 2004) argues that nodes that link different groups in a network (or, in Burt's terminology, nodes that bridge “structural holes”) have advantageous access to information and diverse opportunities. The reverse of high access to diverse cliques of otherwise disconnected nodes is quantified by Burt’s constraint, which is defined as

$$\sum_j c_{ij} = \sum_j (p_{ij} + \sum_q p_{iq} p_{qj})^2,\ i \neq q \neq j$$

where p_{ij} is 1/(the number of links of node i) (assuming that all links have the same weight). This constraint measure is larger when a node is linked with nodes which are linked with one another and the constraint is low for nodes linked with a variety of nodes that are not linked to each other.

Finally, we utilize the clustering coefficient, or the local transitivity, defined as the ratio of actual triplets with each node's partners to all possible triplets with its partners. This measure quantifies the proportion of a node’s partners that are linked together. A large clustering coefficient implies that the node's partners are also highly linked, creating a cluster of nodes. Burt (2004) argues that when the ego-network, or the network of a particular node, is highly clustered, knowledge of the node and its neighbors is largely overlapped so that they cannot learn much from each other. This is related to the argument of Granovetter (1973), "strength of weak ties," that weak ties with outsiders are more helpful to obtain information.

Both Burt’s constraint and local clustering are high when the density of links around the node in focus is higher. The difference between the two measures emerges in the case when a firm has many partners that are connected to another dominant firm. When a firm has many partners who are all connected to another firm, such network composition can be characterized by low clustering (because such structure can be achieved by relatively small number of interconnecting links relative to the number of all possible links between the partners) but high constraint (because one firm dominates the whole network of the firm).

The dependent variables, i.e., sales growth from 2011 to 2012 or 2013, and other control variables, i.e., sales growth from 2006 to 2011, sales per worker in 2011, the number of workers in 2011, the value of total assets in 2011, and firm age, are taken from Osiris.

3.3. Descriptive statistics

The upper rows of Table 2 show summary statistics for the variables related to supply chains. The mean, minimum, median, and maximum number of suppliers are 6.53, 0, 3, and 233, respectively. The mean of the number of domestic is 3.37, indicating that the number of domestic suppliers and that of foreign suppliers do not differ substantially. This is because firms included in the LiveData are mostly publicly listed firms that are more likely to be internationalized to a large extent. The average number of damaged suppliers is 0.32. Looking at the mean of the dummy variable for damaged suppliers, we find 16.6% of all firms in the world in our data are directly connected to suppliers directly damaged by the hurricane. Further, 43.0%, or almost a half, of firms in the world are indirectly connected to directly damaged suppliers within only two steps of supply chain ties. This finding suggests that most firm pairs are indirectly connected within a few steps of supply chain relations is consistent with previous findings using other datasets. For example, Saito (2012) finds that 62% of firms in Japan are connected to firms in the areas hit by the Great East Japan earthquake in 2011, which constitute only 2% of firms, within two steps.

On the other hand, the mean, minimum, median, and maximum number of customers are 8.89, 0, 4, and 196, respectively. The mean of the number of domestic customers is 3.57.

The bottom rows of Table 2 indicate summary statistics of these network measures and other control variables. The median sales growth is 7.7%, whereas the median number of workers and firm age are 2,600 and 22 years, respectively. These figures show that our sample firms are mostly established, large, and growing firms, as we repeatedly mentioned.

4. Results

4.1. Balancing tests

As we mentioned in Section 2.3, we will rely on OLS estimations. To check whether OLS estimations lead to unbiased estimates, we run OLS to test whether supply chain links with damaged suppliers (customers) predict sales growth before the disaster, including only country and industry dummies as additional independent variables. Table 3 shows that either the dummy for any direct link or two-step link with suppliers (customers) directly damaged by the hurricane has no significant correlation with sales growth before the hurricane. This result indicates that direct and indirect links with damaged suppliers are randomly allocated to firms and hence that our key variables of interest, the number of and the dummy for links with damaged suppliers, are uncorrelated with the error term in equation (1). Therefore, our use of OLS estimations can be justified.

4.2. *Benchmark results*

Table 4 shows the results from the benchmark estimations using the number of suppliers in logs as the key independent variables. The dependent variable is sales growth from 2011 to 2012 in columns (1) and (2) to examine immediate propagation effects, while it is sales growth from 2011 to 2013 in columns (3) and (4) to check longer-term effects. Columns (1) and (3) includes local clustering coefficient as a control variable to reflect the finding of the previous literature which finds the negative effect of density measures on performance (Granovetter,1973; Villena et al.,2011). To calculate the local clustering coefficient, however, we need more than or equal to two links and thus have to drop firms with zero or one link from our sample. Since the previous literature in economics does not consider the local clustering coefficient in their estimations, we also try not to include this variable so that we can show this restriction due to missing values in local clustering coefficient does not cause significant bias to the estimation.

The negative and significant effects of links with damaged suppliers in columns (1) and (2) indicate that domestic customers directly connected with suppliers damaged by the hurricane experienced lower sales growth after the hurricane, probably because of the shortage of supplies. The fact that the coefficient in column (3) and (4) are smaller in absolute terms than that in (1) and (2) suggests that the negative propagation effect through supply chains declined in a year, a finding consistent with that of Barrot and Sauvagnat (2016) for domestic supply chains within the US. Further, in (3) and (4), we find that the coefficients on the interaction terms are insignificant, concluding that customers in the US and outside the US are equally affected by the negative shock from their US suppliers damaged by the hurricane. In contrast, in (1) and (2), we observe that the coefficient on the interaction terms are significantly positive and the sizes are large enough to offset the negative coefficient on the single term, implying that there is a larger time lag for customers outside the US to be affected. Compared with the significant negative effect of direct links with damaged suppliers, the effect of indirect 2-step links tends to be positive insignificantly or significantly. Thus, we do not find any propagation of the disaster shock to indirect customers.

In Table 5, we use dummy variables for various types of links with damaged suppliers. The results for direct links with damaged suppliers, shown in the first two rows, are consistent with the results from Table 4. However, the effect of indirect 2-step links with damaged suppliers is now negative and significant in Table 5 column (2), and the interaction term with the non-US dummy is positive and insignificant. Judging from all eight specifications, it is most likely that 2-step links with at least one damaged firm have a negative effect on US customers and non-US customers equally.

On the other hand, Table 6, the benchmark results for the effect on suppliers' sales growth, shows that the upstream propagation from damaged customers to their suppliers has different features from the downstream propagation examined in Table 4 and 5. The columns (1) and (2) show negative and significant effects of links with damaged customers on short-run sales growth, while columns (3) and (4) indicate positive and substantially small significant effect in a longer run. This suggests that suppliers facing demand shocks reduce sales in the short run but may find new customers and thus recover from the demand shock relatively quickly. This is consistent with the finding of Carvalho et al. (2014) which suggests that suppliers are more likely to find new partners to lessen negative effects of disasters than customers. By contrast, 2-

step links with damaged customers have an insignificant effect in the short and long run.

The result of Table 4 and 5 may reflect the difference between the effect of damaged suppliers and damaged customers; the existence of damaged suppliers sometimes suspend the operation of customers which are not directly hit by the hurricane, while that of damaged customers are less likely to halt the operation of suppliers. Another difference is that the propagation within the country and beyond the country is different in the case of demand shocks. In all columns, the result of joint significance test between the coefficient of the number of links with damaged customers and the interaction term cannot deny the possibility of no propagation beyond the country. This implies that exporting does not expose firms to the risk of demand shocks due to disasters.

To test the robustness of the results, we further conduct the same estimation as in the main analysis but instead of links to firms in the disaster area we count links to undamaged US firms elsewhere that had overall similar characteristics as the firms directly hit by Hurricane Sandy. Hereafter, we call the similar unaffected firms placebo firms. We employed Propensity Score Matching (PSM) method, more specifically, nearest one-to-one matching with replacements, to identify the placebo firms. The matching was conducted on firm attributes including age, net sales, total assets, number of employees, pre-disaster sales growth, industry, and their number of links and PageRank to capture the firms' centrality in the supply networks. The results are shown in Appendix A~C. The statistically significant estimates in the placebo models have opposite signs from the estimates in the main models, implying that the reported impacts on supply chains are indeed highly likely to be due to Hurricane Sandy.

Results on some other variables are worth noting. First, the constraint measure of Burt (1992) has a negative significant effect on sales growth in all specifications. This finding is consistent with some previous studies such as Burt (2004), Phelps (2010), and Todo et al. (2016) that found positive effects of diversity of ego-networks on the performance of firms and individuals. Second, the local clustering coefficient always has a negative and significant effect on sales growth. This is consistent with some previous studies such as Granovetter (1973) and Villena et al. (2011) that found negative effects of density of ego networks and strong ties. Third, PageRank and the degree centrality often have a positive effect, indicating that firms located in the center of the global supply chains are more likely to grow faster.

4.3. Heterogeneous effects

Because the negative propagation effect may differ in size depending on characteristics of firms' networks, we examine the possibility of heterogeneity in two ways. First, we check whether the negative effect is alleviated or amplified by other types of networks by incorporating the number of or the dummy variable for supply chain links with damaged suppliers (customers) associated with shareholding or research collaboration links. When suppliers are major shareholders of their customers, or vice versa, damaged suppliers are likely to allocate more from the limited amount of their parts and components to the affiliated customers than to unaffiliated customers to maximize profits of the affiliated firm group. Similarly, when customers are major shareholders of their suppliers, or vice versa, damaged customers under limited operation try to buy their inputs more from the affiliated suppliers. Thus, the negative effect of damaged suppliers (customers) on their affiliated customers (suppliers) through shareholding ties may be smaller than on unaffiliated customers (suppliers). By contrast, when suppliers and customers are engaged in research collaboration, parts and components transacted between them are likely to be specific to the firm pairs. Therefore, substituting for parts and components developed from research collaborations between suppliers and customers or selling them to other firms is more difficult than otherwise. Thus, the negative effect of damaged suppliers (customers) on their customers (suppliers) that engage in research collaboration with the damaged suppliers (customers) may be larger than on other customers (suppliers) without research collaboration. Second, we examine how the structure of each firm's ego-network affects propagation by incorporating the interaction term between the dummy for (number of) links with damaged suppliers (customers) and the local clustering coefficient. We hypothesize that dense networks amplify the level of propagation through various routs within the network of firms which the focal firm has direct links.

The results from the first alternative specification shown in Table 7 indicate that shareholding links are more likely to alleviate negative effects of damaged suppliers, although their longer-run effects are not very clear as column (3) and (4) of Table 7 show. This is probably because damaged suppliers provide more parts and components from their limited stocks to customers affiliated through shareholding ties to maximize total profits of the firm group while in the long run, either stocks run out or production is restarted. However, Table 8 shows that shareholding links do not have any effects on the size of propagation from damaged customers, although we expect damaged customers may buy more inputs from their affiliated suppliers when their demand for inputs is limited in the short run after the disaster. This is probably because the flexibilities of links with customers itself are high enough and thus the priority difference does not have much meaning.

By contrast, research collaboration links tend to amplify the negative propagation effects substantially, probably because research collaboration between suppliers and customers is most likely to be conducted to develop parts and components specific to customers' products and thus it is difficult to find alternative outlets even for suppliers. This is consistent with the finding of Barrot and Sauvagnat (2016), which suggests that disaster damage on one specific-goods supplier causes his direct customers to be worse off.

The results from the second alternative specification shown in Table 9 and Table 10 demonstrate that the negative effect of damaged direct customers is larger when the local clustering coefficient is larger, i.e., the ego network is denser. In a dense sub-network which includes any customers directly damaged by the hurricane, the negative effect of the damaged customer tends to propagate through various paths in the sub-network and thus be intensified. By contrast, the effect of dense networks is insignificant on customers which are not directly hit by the disaster. As our benchmark result suggests, the existence of one damaged supplier is often critical to the performance of customers. Thus, we do not observe a significant effect of dense networks on the size of propagation of disaster shocks from damaged suppliers.

5. Conclusions

In this paper, we take Hurricane Sandy that hit the east coast of the United States in 2012 as a source of negative shocks and examine its indirect effects on the global economy through supply chains. More specifically, using firm-level data on global supply chains, we examine how sales growth of firms in and outside the US changes when their direct and indirect suppliers (customers) are damaged by the hurricane.

Our results show that direct links with damaged suppliers or customers and indirect links with damaged suppliers in two steps of supply chains lower sales growth of firms. Especially, in the case of supply shocks, disaster damage on one supplier is critical, while the impact of demand shocks depends on the number of damaged customers. Besides, we observe that the negative effect on non-US customers is similar in size to the effect on US customers, concluding that negative shocks due to the hurricane propagated to customers indirectly damaged in the US as well as those outside the US through global supply chains. However, our estimation results also show that the indirect demand shock due to the hurricane propagates only within the US.

We further find that the negative effect is heterogeneous in size across firms depending on characteristics of their network. For example, the negative effect is smaller when the supply chain link is associated with a shareholding link in the short run, whereas it is larger when the supply chain link is associated with a research collaboration link. In addition, the negative effect on a firm's sales growth is larger when the supplier's sub-network is dense.

Taken together, our findings imply that firms should diversify their networks for substitutions with taking extra care of the diversity in locations on supply chain networks and geographical locations.

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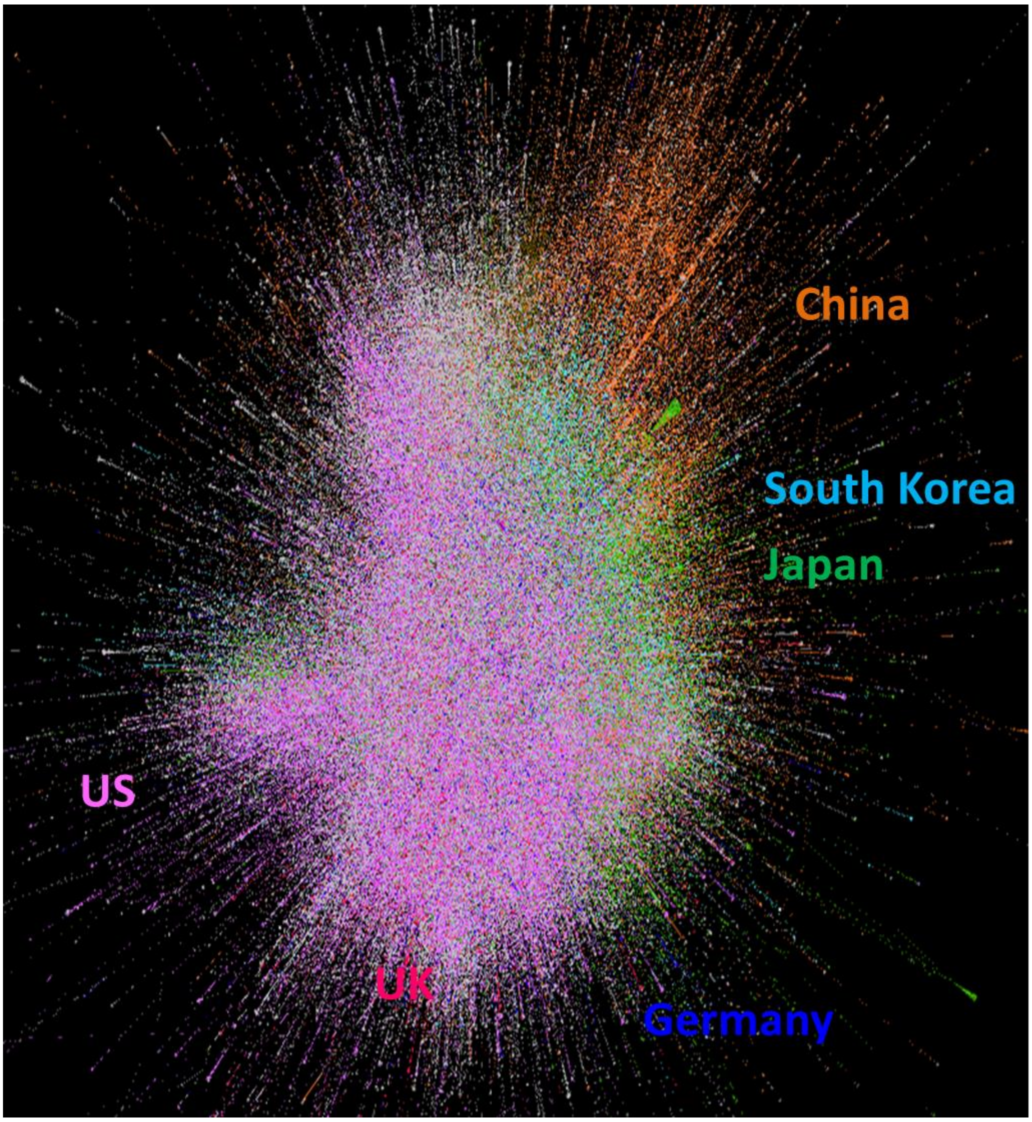
Figure 1: Visualization of Global Supply Chains



Source: LiveData of FactSet Revere

Note: Each dots indicates firms and colored by the location of the headquarters, while links indicate transaction relationships. This is drawn by Force Atlas 2.

Table 1: Number of firms by country of location (Top 10 countries)

country	number of firms	% in total
the United States	1,387	51.66
China	282	10.50
United Kingdom	145	5.40
Japan	110	4.10
Indonesia	98	3.65
France	96	3.58
Germany	82	3.05
Turkey	62	2.31
Israel	43	1.60
Switzerland	35	1.23

Table 2: Summary Statistics

Variable	Mean	S.D.	Min.	Median	Max
Links with suppliers in 2011					
# of suppliers	6.529	14.400	0	3	233
-- in logs	1.375	1.027	0	1.386	5.455
# of domestic suppliers	3.366	9.804	0	1	189
# of suppliers in 2 steps	109.825	254.854	0	11	2586
-- in logs	2.598	2.246	0	2.485	7.858
Links with damaged suppliers in 2011					
# of links with damaged suppliers	0.324	1.16	0	0	25
-- in logs	0.158	0.397	0	0	3.258
Dummy	0.166	0.372	0	0	1
# of 2-step links with damaged suppliers	5.384	13.168	0	0	179
-- in logs	0.861	1.212	0	0	5.193
Dummy	0.430	0.495	0	0	1
# of shareholding links with damaged suppliers	0.001	0.039	0	0	1
-- in logs	0.001	0.027	0	0	0.693
Dummy	0.001	0.039	0	0	1
# of patent application links with damaged suppliers	0.001	0.027	0	0	1
-- in logs	0.001	0.019	0	0	0.693
Dummy	0.001	0.027	0	0	1
Links with customers in 2011					
# of customers	8.891	12.926	0	4	196
-- in logs	1.681	1.104	0	1.609	5.283
# of domestic customers	3.565	6.596	0	1	108
# of customers in 2 steps	147.652	321.236	0	26	3768
-- in logs	3.102	2.240	0	3.296	8.235
Links with damaged customers in 2011					
# of links with damaged customers	0.328	0.890	0	0	11
-- in logs	0.175	0.398	0	0	2.485
# of 2-step links with damaged customers	6.455	14.297	0	0	170
-- in logs	1.033	1.264	0	0	5.142
# of shareholding links with damaged customers	0.004	0.067	0	0	1
-- in logs	0.003	0.046	0	0	0.693
# of patent application links with damaged customers	0.002	0.047	0	0	1
-- in logs	0.002	0.033	0	0	0.693
Other networks measures in 2011					
Burt's constraint	0.192	0.174	0.005	0.127	1.000
Local clustering coefficient	0.057	0.126	0.000	0.009	1.000
PageRank	0.000	0.000	0.000	0.000	0.003
Firm pre-disaster attributes					
Sales growth from 2006 to 2011	0.125	0.317	-0.598	0.077	10.111
Sales per worker in 2011	1046	14003	2	278	496205
-- in logs	5.689	1.043	0.412	5.628	13.115
# of workers in 2011	12269	52720	3	2600	2200000
-- in logs	7.789	1.908	1.099	7.863	14.604
Value of total assets in 2011	4625304	14065988	1156	931061	270441984
-- in logs	13.723	1.878	7.053	13.744	19.416
Firm age	33.309	30.827	6	22	347

Notes: N = 2685. 2-step suppliers (customers) of a firm are defined as suppliers of suppliers (customers of customers) of the firm. Damaged suppliers (customers) are defined as suppliers (customers) in areas hit by the Hurricane Sandy.

Table 3: Balancing Tests

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2006 to 2011			
Dummy for any link with damaged suppliers	-0.00788			
	(0.0167)			
Dummy for any 2-step link with damaged suppliers		0.00525		
		(0.0127)		
Dummy for any link with damaged customers			0.0113	
			(0.0161)	
Dummy for any 2-step link with damaged customers				0.00790
				(0.0133)
Observations	2,685	2,685	2,685	2,685
R-squared	0.064	0.064	0.064	0.064

Notes: Robust standard errors are in parentheses. Industry and country dummies are included, but the results are not reported for the brevity of presentation.

Table 4: Effects of the Number of Damaged Suppliers

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
# of links with damaged suppliers (log)	-0.112***	-0.114***	-0.0259***	-0.0194*
	(0.0200)	(0.0152)	(0.00709)	(0.0110)
# of links with damaged suppliers (log) * non-US dummy	0.132**	0.107**	0.0235	0.0206
	(0.0582)	(0.0437)	(0.0186)	(0.0167)
# of 2-step links with damaged suppliers (log)	0.0235	0.0284	0.0109***	0.0135***
	(0.0153)	(0.0202)	(0.00391)	(0.00336)
# of 2-step links with damaged suppliers (log) * non-US dummy	-0.0184	-0.0107	0.000950	0.000372
	(0.0159)	(0.0137)	(0.00673)	(0.00603)
Constraint	-0.186***	-0.0734**	-0.0932***	-0.0328
	(0.0551)	(0.0299)	(0.0337)	(0.0246)
Local clustering coefficient	-0.242**		-0.0960***	
	(0.0907)		(0.0205)	
PageRank	331.8	312.5	93.97**	88.37**
	(228.3)	(224.5)	(40.79)	(42.67)
Sales growth 2006-11	0.00243	-0.00625	0.0406	0.0260
	(0.0440)	(0.0243)	(0.0393)	(0.0374)
Sales per worker (log)	-0.428***	-0.347***	-0.0773***	-0.109***
	(0.133)	(0.122)	(0.0164)	(0.0257)
# of employees (log)	-0.383***	-0.315***	-0.0636***	-0.0926***
	(0.109)	(0.104)	(0.0118)	(0.0241)
Total assets (log)	0.318***	0.264***	0.0638***	0.0891***
	(0.0902)	(0.0871)	(0.0109)	(0.0204)
Firm age	0.000200	7.61e-05	-6.73e-05	-0.000152
	(0.000210)	(0.000177)	(0.000139)	(0.000125)
Observations	2,685	3,400	2,574	3,268
R-squared	0.065	0.059	0.089	0.130

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies, number of domestic suppliers (log), number of domestic customers (log), number of 2-step suppliers (log), number of 2-step customers (log) are included, but the results are not reported for the brevity of presentation.

Table 5: Effects of the Dummy Variable for Links with Damaged Suppliers

	(1)	(2)	(3)	(4)	(5)
	Dependent variable				
	Sales growth from 2011 to 2012			Sales growth from 2011 to 2013	
Dummy for any link with damaged suppliers	-0.102***	-0.0961***	-0.0972***	-0.0120***	-0.00943**
	(0.0205)	(0.0197)	(0.0163)	(0.00447)	(0.00444)
Dummy for any link with damaged suppliers * non-US dummy	0.106*	0.101*	0.104**	0.0121	0.00893
	(0.0532)	(0.0532)	(0.0506)	(0.0151)	(0.0165)
Dummy for any 2-step link with damaged suppliers		-0.0695**	-0.0649		-0.0258***
		(0.0282)	(0.0391)		(0.00445)
Dummy for any 2-step link with damaged suppliers * non-US dummy			-0.00962		0.00454
			(0.0377)		(0.0159)
Constraint	-0.196***	-0.201***	-0.201***	-0.0968***	-0.0986***
	(0.0567)	(0.0580)	(0.0578)	(0.0355)	(0.0351)
Local clustering coefficient	-0.241**	-0.242**	-0.242**	-0.0936***	-0.0940***
	(0.0944)	(0.0951)	(0.0953)	(0.0203)	(0.0202)
PageRank	312.4*	302.9*	303.5*	98.89**	95.63**
	(182.9)	(172.4)	(171.2)	(40.07)	(37.98)
Observations	2,685	2,685	2,685	2,574	2,574
R-squared	0.065	0.065	0.065	0.088	0.089

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies and the other control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.

Table 6: Effects of the Number of Damaged Customers

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
# of links with damaged customers (log)	-0.149***	-0.138***	0.00774*	-0.000156
	(0.0208)	(0.0164)	(0.00401)	(0.00727)
# of links with damaged customers (log) * non-US dummy	0.149***	0.150***	-0.0180	-0.00566
	(0.0435)	(0.0408)	(0.0189)	(0.0211)
# of 2-step links with damaged customers (log)	0.00999	0.00980	-0.00726	-0.00826*
	(0.00780)	(0.00932)	(0.00467)	(0.00413)
# of 2-step links with damaged customers (log) * non-US dummy	-0.0127	-0.00742	0.0258***	0.0259***
	(0.0146)	(0.0140)	(0.00749)	(0.00793)
Constraint	-0.181***	-0.0630**	-0.0890***	-0.0275
	(0.0548)	(0.0293)	(0.0330)	(0.0241)
Local clustering coefficient	-0.247**		-0.0943***	
	(0.0971)		(0.0194)	
PageRank	299.1*	287.2*	99.24**	99.49**
	(178.2)	(171.2)	(37.65)	(40.11)
Sales growth 2006-11	0.00183	-0.00618	0.0408	0.0266
	(0.0461)	(0.0260)	(0.0387)	(0.0369)
Sales per worker (log)	-0.432***	-0.351***	-0.0769***	-0.109***
	(0.135)	(0.124)	(0.0165)	(0.0258)
# of employees (log)	-0.388***	-0.320***	-0.0644***	-0.0935***
	(0.111)	(0.106)	(0.0116)	(0.0243)
Total assets (log)	0.320***	0.266***	0.0637***	0.0890***
	(0.0919)	(0.0884)	(0.0105)	(0.0206)
Firm age	0.000141	3.29e-05	-7.86e-05	-0.000157
	(0.000241)	(0.000177)	(0.000157)	(0.000135)
Observations	2,685	3,400	2,574	3,268
R-squared	0.065	0.059	0.090	0.131

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies, number of domestic suppliers (log), number of domestic customers (log), number of 2-step suppliers (log), number of 2-step customers (log) are included, but the results are not reported for the brevity of presentation.

Table 7: Heterogeneous Effects of Damaged Suppliers (1)

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
# of links with damaged suppliers (log)	-0.0877**		-0.0213**	
	(0.0371)		(0.0101)	
# of supply chain links with damaged suppliers associated with shareholding links	0.366***		0.0372	
	(0.131)		(0.0338)	
Dummy for any link with damaged suppliers		-0.0667*		-0.00689
		(0.0337)		(0.00707)
Dummy for any supply chain link with damaged suppliers associated with shareholding links		0.216***		0.0149
		(0.0797)		(0.0226)
Observations	2,685	2,685	2,574	2,574
R-squared	0.065	0.065	0.089	0.089

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies and the other control variables used in Table 4 are included, but the results are not reported for the brevity of presentation. Only two firms have supply chain links with damaged suppliers associated with research collaboration links and the customer is common across the two firms. Therefore, we do not include the variable of supply chain links with damaged suppliers associated with research collaboration links (Including it does not affect much on the effect of shareholdings).

Table 8: Heterogeneous Effects of Damaged Customers (1)

	(1)	(2)
	Dependent variable	
	Sales growth from 2011 to 2012	Sales growth from 2011 to 2013
# of links with damaged customers (log)	-0.112**	0.00424
	(0.0467)	(0.00914)
# of supply chain links with damaged customers associated with shareholding links	0.226	0.0258
	(0.138)	(0.0379)
# of supply chain links with damaged customers associated with research collaboration links	-0.322***	-0.439***
	(0.0855)	(0.0266)
Observations	2,685	2,574
R-squared	0.065	0.091

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies and the other control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.

Table 9: Heterogeneous Effects of Damaged Suppliers (2)

	(1)	(2)
	Dependent variable	
	Sales growth from 2011 to 2012	Sales growth from 2011 to 2013
Dummy for any links with damaged suppliers	-0.0665**	-0.00602
	(0.0288)	(0.00676)
Dummy for any 2-step links with damaged suppliers	-0.0712**	-0.0238***
	(0.0282)	(0.00890)
Dummy for any links with damaged suppliers * local clustering coefficient	0.0144	-0.0128
	(0.200)	(0.0805)
Local Clustering Coefficient	-0.239***	-0.0925***
	(0.0848)	(0.0204)
Observations	2,685	2,574
R-squared	0.065	0.089

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies and the other control variables used in Table 4 are included, but the results are not reported for the brevity of presentation. The implication does not change by changing variables from dummy to numbers.

Table 10: Heterogeneous Effects of Damaged Customers (2)

	(1)	(2)
	Dependent variable	
	Sales growth from 2011 to 2012	Sales growth from 2011 to 2013
Dummy for any links with damaged customers	-0.0882*	0.0129*
	(0.0444)	(0.00648)
Dummy for any 2-step links with damaged customers	0.0055	0.0006
	(0.0087)	(0.0086)
Dummy for any links with damaged customers * local clustering coefficient	-0.435***	-0.211*
	(0.117)	(0.120)
Local Clustering Coefficient	-0.215**	-0.0781***
	(0.0949)	(0.0215)
Observations	2,685	2,574
R-squared	0.065	0.089

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Industry and country dummies and the other control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.

Appendix A: Placebo Test Result for Customer's Sales Growth

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
# of links with placebo suppliers (log)	0.0714***	0.0807***	0.00643	0.00367
	(0.0203)	(0.0169)	(0.00873)	(0.00558)
# of links with placebo suppliers (log) * non-US dummy		-0.0337		0.0131
		(0.0702)		(0.0338)
# of 2-step links with placebo suppliers (log)	-0.0696	-0.0811*	0.00500	0.00679
	(0.0446)	(0.0414)	(0.0102)	(0.00785)
# of 2-step links with placebo suppliers (log) * non-US dummy		0.0343*		-0.00516
		(0.0191)		(0.00647)
Observations	2,685	2,685	2,574	2,574
R-squared	0.065	0.065	0.088	0.088

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.

Appendix B: Placebo Test Result for Customer's Sales Growth using Dummies

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
Dummy for any link with placebo suppliers	0.0389***	0.0399***	0.00580	0.00524
	(0.0137)	(0.0137)	(0.00734)	(0.00408)
Dummy for any link with placebo suppliers * non-US dummy		-0.0185		6.77e-05
		(0.0560)		(0.0308)
Dummy for any 2-step link with placebo suppliers	0.0461*	0.0727***	0.00859	0.0153
	(0.0250)	(0.0153)	(0.0180)	(0.0124)
Dummy for any 2-step link with placebo suppliers * non-US dummy		-0.0668*		-0.0167*
		(0.0346)		(0.00963)
Observations	2,685	2,685	2,574	2,574
R-squared	0.064	0.064	0.088	0.088

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.

Appendix C: Placebo Test Result for Supplier's Sales Growth

	(1)	(2)	(3)	(4)
	Dependent variable			
	Sales growth from 2011 to 2012		Sales growth from 2011 to 2013	
# of links with placebo customers (log)	0.201***	0.247***	-0.0286***	-0.0323***
	(0.0534)	(0.0166)	(0.00603)	(0.00386)
# of links with placebo customers (log) * non-US dummy		-0.208***		0.0267
		(0.0453)		(0.0251)
# of 2-step links with placebo customers (log)	0.00174	-0.00999	0.00814	0.00239
	(0.0119)	(0.0140)	(0.00585)	(0.00441)
# of 2-step links with placebo customers (log) * non-US dummy		0.0433**		0.0222**
		(0.0209)		(0.00948)
Observations	2,685	2,685	2,574	2,574
R-squared	0.066	0.066	0.089	0.091

Notes: Robust standard errors clustered at the country level are in parentheses. * **, and *** signify statistical significance at the 10, 5, and 1% level. Control variables used in Table 4 are included, but the results are not reported for the brevity of presentation.