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Robustness and resilience of supply chains during the COVID-19 pandemic

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Abstract

Using a unique firm-level data set from Asia, this study examines what determined the robustness and resilience of supply chain links, that is, the ability of maintaining links and recovering disrupted links by substitution, respectively, when firms faced economic shocks due to the spread of the coronavirus disease (COVID-19). We find that a supply chain link was likely to be robust if the link was between a foreign-owned firm and a firm located in the foreign-owned firm's home country, implying that homophily on a certain dimension generates strong ties and thus supply chain robustness. We also find that firms with geographic diversity of customers and suppliers tended to increase their transaction volume with one partner while decreasing the volume with others. This evidence shows that firms with diversified customers and suppliers are resilient, mitigating the damage from supply chain disruption through the substitution of partners. Furthermore, the robustness and resilience of supply chains are found to have led to higher performance.

KEYWORDS

COVID-19, diversity, homophily, resilience, robustness, supply chains

1 | INTRODUCTION

When the coronavirus disease (COVID-19) pandemic hit economies across the world in 2020, global supply chains, that is, the network of firms through which transactions of intermediate goods and services are made, were widely disrupted because the supply of and demand for goods and services shrank due to 'lockdown' policies that restricted on-site working and consumers' purchasing activities (Di Stefano, 2021). On 18 April 2020, when the level of restrictions peaked, governments in 160 out of 184 countries required workplaces to be closed or imposed work-from-home mandates on certain sectors or categories of workers, and 126 countries required people not to leave home, with some exceptions (Hale et al., 2021). By the end of 2020, the number of countries that required workplaces to be closed and people to stay at home had declined to 117 and 77, respectively, but production activities were still heavily affected by these lockdown policies in many countries. It is notable that these lockdowns affected not only local economies directly but also other economies indirectly through supply chain disruptions.

As supply chains have expanded globally (Baldwin, 2016), economic shocks have often been observed to propagate through supply chains to other regions and countries for two reasons: the customer firms of a firm affected by a shock are indirectly affected due to shortages in the supply of inputs, and the suppliers of such a firm are also affected due to shortages in demand. Barrot and Sauvagnat (2016) found that economic shocks caused by natural disasters in the United States from 1978 to 2013 decreased sales of firms that were not directly hit by the disasters but connected to firms in the disaster areas through supply chains. Carvalho et al. (2021) and Kashiwagi et al. (2021) also confirmed the propagation of economic shocks through supply chains in the case of the Great East Japan Earthquake and Hurricane Sandy in the United States respectively. Boehm et al. (2019) focused on intra-firm input–output linkages between Japanese firms and their subsidiaries in the United States and found international propagation of shocks due to the Great East Japan Earthquake.

The propagation of economic shocks through supply chains due to the COVID-19 pandemic has also been studied in the literature. Guan et al. (2020) simulated how the production of countries would change due to lockdown policies based on world input–output tables at the country–sector level and a macroeconomic model incorporating intersectoral input–output linkages. They found that global production would decline by 40% in their worst-case scenario. Inoue and Todo (2020) took a similar simulation approach but used firm-level, rather than sector-level, data for domestic supply chains in Japan and found that a lockdown in Tokyo would result in a large production decline in other regions that did not have lockdowns because of propagation through supply chains. Inoue et al. (2021) further showed that the substitutability of inputs across suppliers could greatly mitigate the propagation of the COVID-19 shock through supply chains, as found in earlier studies, such as Barrot and Sauvagnat (2016), Carvalho et al. (2021), Kashiwagi et al. (2021).

Using firm-level data for 4433 enterprises collected after the spread of COVID-19, Borino et al. (2021) found that international firms, that is, firms engaging in international trade, were more likely to face difficulty in accessing inputs and thus to reduce sales than domestically confined firms because of the international exposure of the former. However, international firms were also more likely than domestic firms to adopt resilient strategies such as promoting teleworking and online sales and beginning to source from new suppliers because of the connectivity and productivity of the former. Higher resilience of international firms was also observed with respect to the case of Hurricane Sandy by Kashiwagi et al. (2021).

Other studies have examined the effect of the COVID-19 pandemic on international trade. Liu et al. (2021) found that COVID-19 deaths and lockdowns reduced countries' imports from China, empirically demonstrating a negative effect of COVID-19 on trade. More importantly, Hayakawa and

Mukunoki (2021) used data for bilateral trade in intermediate goods and found that an economic shock from COVID-19 in a particular country, measured by the number of COVID-19 cases and deaths, reduced exports from that country and further reduced exports from countries using inputs produced in that country. Their findings clearly confirmed the propagation of the COVID-19 shock through global supply chains.

However, the following two important issues remain unanswered in the literature. First, facing supply and demand shocks due to COVID-19, some supply chain links were disrupted, while others were maintained. Which characteristics of firms and links resulted in the robustness of links has not been examined because existing studies use sector-level trade data or firm-level data without information on suppliers or customers. Second, when firms were challenged by disruptions of links with their suppliers or customers, some were able to substitute the disrupted transactions with transactions with other partners and minimise the negative effect of COVID-19, while others were not. The literature has not investigated what characteristics of firms' own supply chains determined the resilience of firms, that is, their ability to recover from supply chain disruptions, in the case of COVID-19.

Given the shortcomings of the literature, we study these two issues using data for approximately 1400 firms in the Association of Southeast Asian Nations (ASEAN) member countries and India. The data were collected from November 2020 to February 2021, that is, after the first stage of the COVID-19 pandemic, by the Economic Research Institute for ASEAN and East Asia (ERIA) and contain information on the top three suppliers and customers of each firm. The target firms include both domestic and foreign-owned enterprises. We focus on firms in the ASEAN and India because international supply chains are prominent in this region (Ando & Kimura, 2010; Kimura & Obashi, 2016; Obashi & Kimura, 2017). Moreover, the COVID-19 pandemic hit the economies in the target region directly and indirectly through supply chains, for example, due to the lockdown policies in China, a major hub of global supply chains. However, supply chains in East Asia were found to be less vulnerable to the COVID-19 shocks than those in other regions, such as Europe and the Americas, according to Kimura (2021) and Hayakawa and Mukunoki (2021). Therefore, we expect variations in the robustness and resilience across supply chain links and firms in our target region, a setting that allows us to investigate the determinants of supply chains' robustness and resilience to network disruptions.

In the empirical analysis, we focus on the effect of tie strength on robustness and the effect of the geographic diversity of supply chain partners on resilience, obtaining notable findings. First, when a foreign-owned firm was linked with a supplier or customer in its home country, the supply chain link between the two was less likely to be disrupted during the COVID-19 pandemic. In contrast, ownership relationships in addition to supply chain links did not lead to such a mitigation effect, perhaps due to the ease with which short-run adjustments could be made to intra-firm transactions. These findings suggest that some form of homophily (the tendency of agents to form a link with those with similar attributes) creates strong ties and thus robustness of links. Second, when a firm was linked with suppliers and customers that were diversified across countries, the firm was more likely to substitute other partners for partners delinked by the COVID-19 shock. This evidence indicates that the geographic diversity of suppliers and customers can promote firms' resilience to supply chain disruptions. Finally, robustness and resilience increased the performance of firms in the short and long run after the first stage of the pandemic.

This study contributes to the literature in the following three ways. First, because of the COVID-19 pandemic and other recent natural disasters that caused supply chain disruptions, supply chain resilience is a key strategic issue for firms (Sharma et al., 2020). This study adds to the literature evidence of how supply chains' robustness and resilience to economic shocks, particularly those that hit multiple countries, such as the COVID-19 emergency, can be achieved. Second, we contribute to the more general literature on how networks are formed and eliminated. How links among agents are formed and eliminated has been extensively examined in the empirical literature on network formation (Snijders et al., 2010), but substitution of links in the wake of the exogenous elimination of some links, particularly in the context of supply chains, has not been studied. Finally, we show that the strength of links and the geographic diversity of partners indirectly improve the performance of agents through the robustness and resilience of their links. This conclusion is in line with the findings of existing studies on the effect of network structure on performance, such as Coleman (1988); Iino et al. (2021); Rost (2011); Todo et al. (2015).

2 | CONCEPTUAL FRAMEWORK AND HYPOTHESES

2.1 | Propagation of economic shocks through supply chains

Existing studies find both upstream and downstream propagation through supply chains. For example, Barrot and Sauvagnat (2016) and Boehm et al. (2019) examined how economic shocks to suppliers due to natural disasters propagate to their customer firms because of input shortages. In addition to such downstream propagation, Carvalho et al. (2021) and Kashiwagi et al. (2021) found upstream propagation from customers to their suppliers because of shortages of demand for inputs. Hayakawa and Mukunoki (2021) confirmed the existence of upstream and downstream propagation from countries affected by the COVID-19 pandemic through global supply chains.

The recent literature on the economics of networks has found that the structure of inter-firm networks can substantially affect how economic shocks propagate (Acemoglu et al., 2015; Elliott et al., 2014; Joya & Rougier, 2019). The literature on supply chains has also found that the degree of propagation of economic shocks through supply chains depends on their network structure, as shown below in detail. This study particularly focuses on two types of propagation effects of economic shocks through supply chains, that is, robustness and resilience, defining robust supply chains as those that are less likely to be disrupted by a shock and resilient supply chains as those that can recover quickly from disruptions, following Miroudot (2020) and Woods (2015).

2.2 | The positive effect of strong ties on robustness

The literature finds that supply chain links can be more *robust* when suppliers and customers are strongly connected. A typical type of strong tie in supply chains is supplier–customer relationships known as *keiretsu* in Japan. In *keiretsu* relationships, suppliers and customers are often linked through other channels, such as inter-firm shareholding, knowledge and information sharing and collaboration in research and development activities (Aoki, 1988; Dyer & Nobeoka, 2000). These multi-layered and thus strong relationships promote robustness because they generate large mutual benefits from sustainable supply chains. In other words, if a supplier lowers its production capacity because of a disaster, including a pandemic, the supplier is more likely to prioritise its supplies to strongly connected customers than to other customers. Even when a strong supply chain link is disrupted because of a large shock, it is more likely than a weak link to be reconnected. In the event of the Great East Japan Earthquake, many firms outside the disaster area supported their supply chain partners to minimise the negative effect of supply chain disruptions and continued the relationships afterwards (Iwao & Kato, 2019; Todo et al., 2015). Based on the argument above, this study examines the effect of ownership relationships between suppliers and customers on the robustness and resilience of their supply chain links.

Another source of strong ties is homophily, the tendency of agents to connect with others who are socially and economically similar or geographically close, which has been found to be a major driving force of social network formation (Baccara & Yariv, 2013; Currarini et al., 2009, 2016; Fafchamps & Gubert, 2007; Hoshino et al., 2020; Kets & Sandroni, 2019; McPherson et al., 2001). Such homophilous relationships promote trust among agents because of psychological proximity (Coleman, 1988). In a prisoner's dilemma where agents betray each other in the 'rational' equilibrium, trust among agents ensures mutual economic benefits of cooperation and thus promotes long-term and strong relationships. The positive effect of trust on economic outcomes has been found in empirical studies, such as Karlan (2005) and Knack and Keefer (1997).

In our study, we particularly pay attention to homophily in terms of the country of origin as a determinant of supply chain robustness. When a foreign-owned firm is linked with a partner in its home country, decision makers in the firms are more likely to feel psychological proximity and to trust each other and thus to maintain their relationships even in the wake of an economic shock. For example, when a customer faces a negative production shock, it may maintain transactions with its trustworthy suppliers while reducing transactions with others because the customer expects reciprocal behaviour from the supplier if the latter faces a shock in the future.

Based on the literature review and arguments above, we propose the following hypotheses to be tested in the link-level estimations, that is, estimations that examine how the robustness of supply chain links is determined.

Hypothesis 1 *When an economic shock hits supply chains, the transaction volume between two firms connected through the supply chains is less likely to shrink if the firms are also connected through a shareholding relationship.*

Hypothesis 2 *When an economic shock hits supply chains, the transaction volume between two firms connected through the supply chains is less likely to shrink if the respondent firm is foreign owned and is linked with the supplier or customer in its home country.*

2.3 | Possible negative effects of strong ties on robustness

Strong supply chain relationships may have several disadvantages. First, strong supply chain links are often associated with specific inputs developed by strongly connected suppliers and customers, as we typically observe in *keiretsu* (Dyer & Nobeoka, 2000). Therefore, when a firm reduces production due to a natural disaster or lockdown, it is difficult for its suppliers and customers to find substitutes. Second, when a firm is densely linked with its partners (i.e. its partners are also linked with each other), an economic shock can circulate among the densely linked firms. Inoue and Todo (2019a, 2019b) showed that when supply chains include loops in a complex manner, the propagation of negative shocks is far greater than when their structure is tree-like or simply directional flows from upstream to downstream without any loop. Accordingly, the negative effect on suppliers and customers can be quite large and long-lasting when they are strongly linked.

Consistent with these contrasting theoretical predictions on the role of strong ties, the relevant empirical evidence is mixed. Boehm et al. (2019) found that economic shocks due to the Great East Japan Earthquake propagated to subsidiaries of Japanese firms located in the United States, although the authors did not compare the degree of propagation through supply chains with and without shareholding relationships. Kashiwagi et al. (2021) showed that the US firms lowered their sales more after Hurricane Sandy when they were linked with suppliers in the disaster area through both supply chains and shareholding relationships than when they were linked through only supply chains. They also found that the propagation effect was larger when the US firms were more densely linked with their suppliers and customers. All these findings suggest that firms with strong supply chain ties are less robust than those without such ties. In contrast, Kashiwagi et al. (2021) showed that the propagation effect from customers in the disaster area could be mitigated when customers and their suppliers are linked with shareholding relationships, suggesting robustness due to strong ties. Therefore, strong supply chains may or may not be robust, depending on the situation or detailed characteristics of the tie strength. If the negative effect of the strong ties surpasses its positive effect, hypotheses 1 and 2 will be rejected.

Alternatively, strong supply chain ties may be more flexible than weak and thus footloose ties. For example, when a firm faces a reduction in production because of the COVID-19 pandemic, it may prioritise arm's length transactions with its clients without any ownership relationship rather than intra-firm transactions with its clients with ownership relationships. This is because the former transactions cannot recover easily once destroyed by a shock while the latter can because of the smaller short-run adjustment costs. If this is the case, as suggested by the literature on supply chain resilience (Ali et al., 2017; Azadeh et al., 2014; Crum et al., 2011; Gunasekaran et al., 2015; Pereira et al., 2014), hypotheses 1 and 2 will also be rejected.

2.4 | The effect of diversity of production sites on robustness

The robustness of the supply chain links of a particular firm is directly affected by its own production. When the production sites of a firm are geographically diversified across countries, whether its production is affected by the propagation effect through supply chains depends on the following two forces. On the one hand, when a firm with production sites across countries faces multi-country economic shocks, the probability that any of its production sites is affected by the shocks – and, thus, that its production declines – increases. On the other hand, if a reduction in the production of one of the firm's establishments can be mitigated by a production increase in another that is not directly affected by a shock, the total production of the firm may not decline. In contrast, if the production sites of a firm are concentrated in a country, the probability that its production sites are affected by the shock is low, but once affected, substitution across production sites is impossible. This consideration leads to the following conditional hypothesis.

Hypothesis 3 *When an economic shock hits supply chains, the transaction volume between two firms connected through supply chains is more or less likely to shrink if any of the firms diversifies its production sites geographically, depending on the magnitude of the concentration or substitution effect of geographic diversity.*

2.5 | The effect of the diversity of supply chain partners on resilience

A major factor in supply chain *resilience* found in the literature is the substitutability of inputs and suppliers. When a supplier of a particular input is damaged by a disaster or stops operations because of a lockdown, its customer firm can recover quickly from supply chain disruptions if the customer can easily find a substitute partner to replace the disrupted supply. Barrot and Sauvagnat (2016) found that input specificity results in substitution difficulties for damaged supply chain partners and thus magnifies propagation. Inoue and Todo (2019a, 2019b) used simulation on the actual supply chain data of more than 1 million firms in Japan and found that substitution of suppliers largely affected propagation of shocks through supply chains after the Great East Japan Earthquake in 2011. Inoue et al. (2021) and Guan et al. (2020) reached the same conclusion, simulating the case of supply chain disruptions in the COVID-19 pandemic in 2020 with firm- and country–sector-level models respectively.

One way to increase input substitutability is to diversify partners. Kashiwagi et al. (2021) examined how the economic shocks of Hurricane Sandy, which hit the United States east coast in 2012, propagated through global supply chains and found that firms located in the United States and linked with suppliers and customer firms in the disaster area had lower post-disaster sales, most likely due to supply chain disruptions. However, the negative propagation effect was alleviated for firms located outside the United States and was not observed for firms located in the United States and linked with firms outside the United States. These findings imply that firms with diversified partners in the world market can minimise the impact of supply chain disruptions by finding substitutes relatively easily. The conclusion of Kashiwagi et al. (2021) is consistent with the conclusion of Borino et al. (2021) that international firms were more resilient to the COVID-19 shock because of their connectivity to the world market. Ando and Hayakawa (2021) used international trade data at the country–pair–product level and found a negative effect among exporters of machinery parts of the number of COVID-19 cases on exports of machinery from countries that import parts from the infected countries. They further found that the negative effect through global supply chains was mitigated when exporter countries import parts from more diversified countries, confirming the importance of supplier diversity.

Kashiwagi et al. (2021) also revealed that upstream propagation from customers to suppliers can be mitigated when suppliers are internationalised. This is possibly because firms can find substitutes for damaged customers when they are connected to various customers in the world market. In other words, diversifying customers, in addition to suppliers, can generate resilience to economic shocks.

In line with these studies, the related literature on supply chain management emphasises the importance of flexibility in supply chain resilience (Ali et al., 2017; Azadeh et al., 2014; Crum et al., 2011; Gunasekaran et al., 2015; Pereira et al., 2014). Diversification of partners provides firms flexibility if they need to modify partners in the wake of supply chain disruptions.

Therefore, regarding the firm-level estimations, we propose the following hypothesis.

Hypothesis 4 *When an economic shock hits supply chains, the reduced transaction volume of a firm with its partners is more likely to be substituted by an increase in transactions with another partner if the firm's supply chain partners are more diversified geographically.*

3 | DATA

3.1 | Firm-level survey

ERIA commissioned Deloitte Consulting Pte Ltd. (Deloitte) to conduct a survey on the impact of the COVID-19 pandemic on business activities and supply chains (hereafter, the survey) in the ASEAN Member States (Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam) and India. The primary purpose of the survey is to comprehend the degree of the impacts of COVID-19 on supply chains in East Asia and the ASEAN region. The targeted firms include both locally owned firms and multinational enterprises.

The survey questionnaire comprised three parts. The first part covered the impact of COVID-19 on business performance and outlook. Specifically, the questionnaire asked about respondent firms' sales, exports and operating profits in 2020 and their outlook for operating profits and employment in the next 1–2 years. The first part also asked whether the COVID-19 pandemic caused changes in operating profits. The second part covered the impact of COVID-19 on supply chains. In particular, the respondent of each firm answered questions about the attributes of the firm's top three customers and suppliers (including their locations, industries and firm size) and whether and why the firm changed (shrank/did not change/expanded) or would change the transaction amount with each of its top three customers and suppliers. The third part covers the respondents' evaluation of the government support in response to COVID-19. The responses from this part are not used in this study. All the survey questions are available in Oikawa et al. (2021). The respondents answered the questionnaire online and spent approximately 30 minutes completing the survey.

One of the challenges involved in administering the survey was how to recruit respondents to complete a lengthy questionnaire when firms faced difficult economic circumstances because of the COVID-19 pandemic and had already been targeted for several COVID-19–related questionnaire surveys.[1] To respond to this challenge, we designed multiple survey channels to recruit respondents. The first channel was Deloitte's customer network. The primary target firms through this channel were multinational or relatively large-scale companies. Deloitte sent the online questionnaires to 3269 companies operating in the ASEAN and India and collected responses from 412, or 12.6%. The second survey distribution channel was industry associations. We approached several local and foreign industry associations, including the Japanese and British chambers of commerce in our target countries. These industry associations distributed the online questionnaire to their member firms. The estimated number of firms targeted through this second channel was 11,199, and the number of respondents was 93 (0.8%). The third distribution channel, which we used to reach small and medium-sized enterprises, was business-to-business market research companies, since the above two channels had access to relatively large-scale companies. For this purpose, we commissioned the SIS International Research and Market Xcel Data Matrix, which are experienced in the East Asia and ASEAN regions. These two research companies distributed the questionnaire to 62,620 companies, and they gathered responses from 1578 respondents (2.5%).

The survey was split into two phases to collect and analyse the responses efficiently. The first phase covering Malaysia, Singapore and Thailand was carried out from 17 November 2020 to 8 January 2021. The second phase targeted the other eight countries and took place from 1 December 2020 to 16 February 2021.

3.2 | Variable construction

Using the information about the top three customers and suppliers of each respondent firm, we construct two link-level data sets: one for the supply chain flows from our sample firms to their top three customers and the other for the flows from their top three suppliers to the sample firms. Using the data set for links with customers, we define the dependent variable that represents the resilience of each link, $SHRINKc_{ij}$, as a dummy variable that takes a value of 1 if transactions between firm i and its customer j were suspended or their volume decreased in and after 2020 in comparison with that in

[1]The Asian Development Bank (ADB) conducted a survey of Philippine businesses in April and May 2020 (ADB, 2020). The Japan External Trade Organization (JETRO) carried out a survey of Japanese affiliated enterprises in Southeast Asia in August and September 2020 (JETRO, 2021). The American Chamber of Commerce in Indonesia (AmCham Indonesia) and ERIA conducted a rapid survey for AmCham Indonesia's member firms in April 2020 and undertook a more detailed survey of foreign firms in ASEAN in collaboration with 24 chambers and business organisations in September 2020 (AmCham Indonesia and ERIA, 2020).

2019 due to the COVID-19 pandemic. Specifically, this variable is constructed from a question about the change in transactions with each of the top three customers, with multiple-choice response options of 'suspension of transactions', 'decrease in transactions', 'no change in transactions' and 'increase in transactions', and another question about the reason for the change. If the respondent firm chose 'suspension of transactions' or 'decrease in transactions' and chose COVID-19 as the reason for the change, *SHRINKc* is set to 1.

In addition, our key independent variables are the following measures of the strength of the link between the respondent firm and its customer. First, HOM_FDI_C is a dummy variable that takes a value of 1 if the respondent firm is foreign owned and if its home country and the country where its customer is located are the same. Second, OWN_C and $OWNED_C$ are dummy variables that take a value of 1 if the customer owns or is owned by the respondent firm respectively.

Using the data set for links with suppliers, we define $SHRINK_S$, HOM_FDI_S, OWN_S and $OWNED_S$ in the same way (the subscripts C and S stand for customers and suppliers respectively).

In the firm-level analysis, our key dependent variables are RES_k, where $k = C, S$ or measures of the *resilience* of firms' links with customers and suppliers. RES_C is a dummy variable that takes a value of 1 if, while the transaction volume of the respondent firm with any of its top three customers shrank because of COVID-19, its transaction volume with another increased. In addition, we define measures of the *robustness* of supply chains of the respondent firm, ROB_k, where $k = C, S$, which are used in alternative specifications. ROB_C is a dummy variable that takes a value of 1 if the transaction volume of the respondent firm with any of the top three customers did not shrink because of COVID-19. RES_S and ROB_S are defined similarly using the relationships of the respondent firm with the top three suppliers.

As key independent variables in the firm-level analysis, we construct two types of measures of geographic diversity of customers/suppliers of each respondent firm. First, $DIVERS_C$ and $DIVERS_S$ are the number of countries where the top customers and suppliers are located respectively. Because we focus on the top three customers and suppliers of each respondent firm, the value of these variables is one, two or three. Second, in addition to the information on the top three customers of each respondent firm, our data include information on the share of sales, input purchases and production by country (and by region outside Asia). Using this information, we define HHI_C and HHI_S as the HHIs of the shares of sales (when we focus on relationships with customers) and input purchases (when we focus on relationships with suppliers), respectively, at the country level. Because HHIs measure the degree of concentration, these variables are considered to indicate the reverse of geographic diversity of customers and suppliers. In addition, we also construct HHI_P, the HHI of the share of production at the country level.

In both the link- and firm-level analyses, we include the attributes of each respondent firm as controls. These are the number of workers, firm age, dummies for types of firm (holding company, branch office, subsidiary or independent company), dummies for business functions (multiple choices among sales, procurement and production), a dummy for listed firms, a dummy for foreign-owned firms, dummies for the home country if foreign owned, a dummy for firms managed by owners and country–industry dummies. In the link-level analyses, we also incorporate the attributes of each customer/supplier, such as categories for the number of workers (19 or less, 20–99 or 100 or more), dummies for the home country if the firm is foreign owned and country–industry dummies for the customer/supplier.[2] Because the total number of home countries of foreign-owned firms in our sample is quite large, we simplify them into six categories: Japan, China, ASEAN, the United States, Europe and others. Although our survey was conducted for 3 months from 17 November 2020 to 16 February

[2]Alternatively, we could include respondent-firm fixed effects. However, because each respondent firm has at most three links due to data limitations, the variations within the respondent firm are not large. Therefore, we do not use respondent-firm fixed effects in our analysis.

2021, the survey of firms in each of the 11 target countries was completed in approximately 2 months (Section 3.1). Therefore, the country–industry dummies used in our analysis capture the time-specific fixed effects that may affect the dependent variables. These attribute variables are taken directly from the responses to the survey.

3.3 | Descriptive statistics

Although the total number of respondent firms is 1578, some firms did not respond to questions about their supply chain partners. After dropping these firms, our firm-level sample for the analysis of the resilience of links with customers and suppliers consists of 1416 and 1316 firms respectively. Using the supply chain information of these firms, we obtain 4269 and 3931 links with customers and suppliers respectively.

Tables 1 and 2 show the distribution of countries and industries, respectively, in the customer-link sample. Because we use country–industry dummies in our estimations, our industry categories are relatively broad: manufacturing, wholesale and retails, communication and software, transportation, business services and others. More than one third of firms are located in India, whereas approximately 10% are located in Singapore, Thailand, Indonesia and the Philippines. In the survey, we did

TABLE 1 Country distribution of respondent firms

Country	Frequency	Percentage
Singapore	150	10.59
Thailand	132	9.32
Malaysia	96	6.78
Indonesia	149	10.52
Philippines	129	9.11
Vietnam	114	8.05
Cambodia	50	3.53
Lao PDR	8	0.56
Myanmar	27	1.91
Brunei	13	0.92
India	548	38.70
Total	1416	100.00

Note: The percentages may not total 100% due to rounding.

TABLE 2 Industry distribution of respondent firms

Industry	Frequency	Percentage
Manufacturing	410	28.95
Wholesale, retail	118	8.33
Communications, software	296	20.90
Transportation	81	5.72
Business services	257	18.15
Others	254	17.94
Total	1416	100.00

Note: The percentages may not total 100% due to rounding.

TABLE 3 Distribution of home countries of foreign-owned respondent firms

Country	Frequency	Percentage
Japan	132	29.93
United States	86	19.50
Singapore	33	7.48
United Kingdom	27	6.12
France	19	4.31
Germany	19	4.31
Australia	11	2.49
Switzerland	10	2.27
India	9	2.04
Netherlands	9	2.04
Malaysia	8	1.81
Hong Kong	7	1.59
Taiwan	6	1.36
Thailand	6	1.36
Vietnam	6	1.36
Others	53	12.04
Total	441	100.00

Note: The percentages may not total 100% due to rounding.

not necessarily focus on the manufacturing sector because service industries are also involved in global supply chains. For example, the reduction in demand in the retail and wholesale sector due to lockdowns should have affected production in upstream manufacturing sectors. Lockdowns usually restrict the restaurant and tourism industry and hence affect their upstream industries, such as the food and transportation industries. As a result of our broad focus, the share of manufacturing firms is highest at 29%, followed by the communications and software industry (21%) and the business services industry (18%). Some 441 firms, or 31%, among the 1416 in the customer-link sample are foreign owned, with 30%, 20% and 7.5% of the foreign-owned firms primarily owned by Japanese, US, and Singaporean firms respectively (Table 3). Customers and suppliers of the respondent firms are located mostly in the ASEAN and India, while some are outside the region: 8% of their customers are in the United States, 5% are in Europe, 3% are in Japan and another 3% are in China (panel A of Table 4). The distribution of countries of suppliers is similar (panel B).

Table 5 shows the summary statistics of variables in the link-level data. In 31% of the links with major customers or suppliers, transactions declined because of the spread of COVID-19. In 6.9% and 7.6% of the links with customers and suppliers, respectively, the home country of the respondent firm is the same as the location of the partner if the respondent firm is foreign owned. Finally, in 9%–13% of the links, the pair of firms is also linked through capital ownership.

Summary statistics of the variables used in the estimations using firm-level data are shown in Table 6. Nine and seven per cent of the firms display resilient links with customers and suppliers respectively (see *RESc* and *RESs*) – that is, their transactions with a major partner increased, while those with another decreased. The minimum of the three HHIs is 0 because they are defined to be 0 when the respondent firm did not provide any information about the shares of country-level sales, input procurement and production. To control for the effect of the HHIs of value 0, we include dummies for these observations in all estimations. The average number of countries where the top three customers/suppliers are located

TABLE 4 Country distribution of customers and suppliers

(A) Customers			(B) Suppliers		
Country	**Frequency**	**Percentage**	**Country**	**Frequency**	**Percentage**
India	1142	26.75	India	1140	29.00
Indonesia	400	9.37	Indonesia	307	7.81
United States	350	8.20	United States	280	7.12
Singapore	293	6.86	China	269	6.84
Thailand	293	6.86	Singapore	265	6.74
Philippines	282	6.61	Malaysia	248	6.31
Malaysia	275	6.44	Thailand	244	6.21
Europe	202	4.73	Europe	197	5.01
Vietnam	186	4.36	Philippines	190	4.83
Japan	145	3.40	Japan	177	4.50
China	139	3.26	Vietnam	176	4.48
Cambodia	103	2.41	Cambodia	71	1.81
Myanmar	80	1.87	Myanmar	45	1.14
Republic of Korea	36	0.84	Hong Kong	42	1.07
Brunei Darussalam	35	0.82	Republic of Korea	39	0.99
Hong Kong	30	0.70	Taiwan	28	0.71
Lao PDR	20	0.47	Brunei Darussalam	26	0.66
Taiwan	19	0.45	Lao PDR	21	0.53
Others	239	5.60	Others	166	4.23
Total	4269	100.00	Total	3931	100.00

Note: The percentages may not total 100% due to rounding.

TABLE 5 Summary statistics (link-level data)

Variable	Definition	*N*	Mean	SD	Min.	Max.
SHRINKc	=1 if transactions with the customer shrank	4269	0.305	0.460	0	1
HOM_SIZEc	=1 if the firm size of the firm and its customer is similar	4269	0.662	0.473	0	1
HOM_FDIc	=1 if the home country of the FDI firm is the same as the location of the customer	4269	0.0693	0.254	0	1
OWNc	=1 if the customer owns the firm	4269	0.112	0.316	0	1
OWNEDc	=1 if the customer is owned by the firm	4269	0.126	0.332	0	1
SHRINKs	=1 if transactions with the supplier shrank	3931	0.311	0.463	0	1
HOM_SIZEs	=1 if the firm size of the firm and its supplier is similar	3931	0.605	0.489	0	1
HOM_FDIs	=1 if the home country of the FDI firm is the same as the location of the supplier	3931	0.0763	0.266	0	1
OWNs	=1 if the supplier owns the firm	3931	0.0911	0.288	0	1
OWNEDs	=1 if the supplier is owned by the firm	3931	0.0908	0.287	0	1

Abbreviations: FDI, foreign direct investment, SD, standard deviation.

TABLE 6 Summary statistics (firm-level data)

Variable	Definition	*N*	Mean	SD	Min.	Max.
RESc	=1 if transactions with a major customer shrank while transactions with another increased	1416	0.0911	0.288	0	1
EXPANDs	=1 if transactions with a major customer increased	1416	0.476	0.500	0	1
ROBs	=1 if transactions with any major customer did not shrink	1416	0.567	0.496	0	1
DIVERSc	# of countries of major customers	1416	1.603	0.819	1	3
HHIc	HHI of country-level shares of sales	1416	0.466	0.404	0	1
RESs	=1 if transactions with a major supplier shrank while transactions with another increased	1316	0.0714	0.258	0	1
EXPANDs	=1 if transactions with a major supplier increased	1316	0.403	0.491	0	1
ROBs	=1 if transactions with any major supplier did not shrink	1316	0.563	0.496	0	1
DIVERSs	# of countries of major suppliers	1316	1.648	0.833	1	3
HHIs	HHI of country-level shares of input purchases	1316	0.473	0.414	0	1
HHIp	HHI of country-level shares of production	1416	0.431	0.449	0	1.620
L	Number of workers	1416	5868	33,566	0	550,000
ln*L*	Number of workers +1 in logs	1416	5.209	2.574	0	13.22
AGE	Firm age	1416	24.92	32.44	0	466
ln*AGE*	Firm age + 1 in logs	1416	2.755	1.040	0	6.146
FDI	Dummy for foreign-owned firms	1416	0.321	0.467	0	1
Listed	Dummy for listed firms	1416	0.256	0.437	0	1
Owner	Dummy for owner-managed firms	1416	0.646	0.478	0	1

Abbreviations: HHI, Herfindahl–Hirschman index, SD, standard deviation.

(*DIVERSc* and *DIVERSs*) is 1.6. Moreover, *DIVERSs* is 1 for 58% of firms, 2 for 18% and 3 for 23%, whereas *DIVERSc* is 1 for 62%, 2 for 17% and 3 for 21%. The distribution of these variables indicates that firms diversify their supply chain partners across countries to some extent and that the variation in the degree of diversity is sufficiently large. The average number of workers and firm age are 5868 and 24.9 respectively. The minimum number of workers is 0, possibly because these firms are family owned without any employees. Accordingly, before we take the log of the number of workers, we add 1 to the number of workers. Similarly, because firm age can be 0 for newly born firms, we add 1 to firm age and take the log. It should also be noted that the maximum number of workers is 550,000 and that its top 1 percentile is 138,000. Although its mean is 5867, its median is 151.5. These figures indicate that our sample includes some extremely large firms. To check whether this skewed distribution leads to biased results, we run all the estimations described below using both the full sample and the subsample that excludes the top 1% of firms in terms of the number of workers and those with 0 workers, and we obtain essentially the same results. Therefore, in the following, we report only the results from the full sample, while those from the subsample are presented in Appendix (Tables A1–A4).

4 | EMPIRICAL METHODOLOGY

To test the hypotheses in Section 2 using the data described in Section 3, we run two types of estimations: one at the supply chain link level (i.e. bilateral firm level) to test hypotheses 1-3 and the other at the firm level to test hypothesis 4.

4.1 | Link-level analysis

Our link-level analysis employs the following linear probability model:

$$SHRINKc_{ij} = \beta_0 + \beta_1 W_i + \beta_2 X_{ij} + \beta_3 Z_j + \varepsilon_{ij}, \tag{1}$$

where $SHRINKc_{ij}$ is the dummy variable that takes a value of 1 if transactions between firm i and its customer j were suspended or its volume decreased in and after 2020 in comparison with those in 2019 due to COVID-19, as defined in Section 3.2. Because of the data limitation explained in Section 1, firm j is one of the top three customers of firm i. W_i, X_{ij} and Z_j are vectors of variables for reporting firm i, the supply chain link between i and j and partner firm j respectively. To test hypotheses 1 and 2, vector X_{ij} includes several variables that measure the strength of the link between i and j, HOM_FDI_C, OWN_C and $OWNED_C$. To test hypothesis 3, vector W_i includes the reverse measure of the diversity of the production sites of firm i, *HHIp*. W_i also includes control variables, including country–industry dummies for firm i, whereas Z_j includes country–industry dummies for firm j. These two types of country–industry dummies control for the effect of lockdowns in industries and countries of the respondent firm and its partner and other country–industry-specific effects. Other control variables are fully explained in Section 3.2. When we focus on the resilience of links with suppliers, we replace $SHRINKc_{ij}$ with $SHRINKs_{ij}$ and, similarly, the independent variables for the link between firm i and its customer j with those for the link between firm i and its supplier j.

We estimate Equation 1 by ordinary least squares (OLS) estimation, assuming that the independent variables are either exogenous or were predetermined before the pandemic. Cluster robust standard errors at the level of firm i's country and industry and firm j's country are used.

4.2 | Firm-level analysis

We also estimate the following linear probability model at the firm level:

$$RESc_i = \delta_0 + \delta_1 V_i + e_i, \tag{2}$$

where $RESc_i$ is the dummy variable for firm i's resilience to upstream supply chain shocks from its customers. Specifically, it is 1 if firm i decreased its volume of transactions with any of its top three customers after the spread of COVID-19, while it increased its transaction volume with another customer (Section 3.2). In other words, this dummy is 1 when the firm could substitute a disrupted customer with another one and thus can be considered resilient. To test hypothesis 4, vector V_i includes a measure of the diversity of customers, $DIVERS_C$. V_i also includes the control variables explained in Section 3.2 and country–industry dummies for firm i and country–industry dummies for each of its top three partners. As in the link-level analysis, these country–industry dummies control for the direct effect of lockdowns. In this estimation, we also rely on OLS and use robust standard errors at the country–industry level.

One shortcoming of the estimation of Equation (2) is that *RESc* is 0 for two completely different types of firms: those whose transaction volume shrank with all of their top three customers and those whose transaction volume did not shrink with any of their top three customers (or those whose *ROBc* defined in Section 3.2 is 1). To distinguish between the two types of firms, we create a categorical variable, $RESROBc_i$, that is 1 if $RESc_i = 1$, 2 if $ROBc_i = 1$, and 0 otherwise, and estimate how the value of *RESROBc* is determined using a multinomial logit model. This estimation enables us to estimate supply chain characteristics on vulnerability (i.e. transactions with all major customers shrank), resilience (some transactions shrank while others expanded) and robustness (transactions with any major customer did not shrink) separately in a unified framework.

In addition to the resilience and robustness to upstream supply chain shocks, we examine the resilience and robustness to downstream shocks from suppliers using the same framework, but customers are replaced with suppliers. More precisely, the dependent variable in Equation (2) is RESsi, the dummy variable that takes the value of 1 if firm *i* decreased its volume of transactions with any of its top three suppliers after the spread of COVID-19, while it increased its transaction volume with another supplier. In addition, we use *RESROBs*, which is the supplier version of *RESROBc*, in a multinomial logit estimation. In the three types of estimations, the key independent variable is a measure of the geographic diversity of suppliers or the number of countries where the firm's top three suppliers are located.

4.3 | Econometric issues

As mentioned in Sections 4.1 and 4.2, we rely on simple OLS and multinomial estimations mainly because of data limitations. In this section, we note possible biases and their directions in our estimations.

First, our analysis is based on a firm-level survey organised by ERIA and conducted by Deloitte, as explained in Section 3.1. One important purpose of this survey was to provide policymakers an immediate view of the economic impacts of the COVID-19 pandemic in the ASEAN and India amid the turmoil of the pandemic (Oikawa et al., 2021). Accordingly, the target firms were not randomly selected but were selected through several channels easily available to ERIA and Deloitte (Section 3.1). As a result, respondent firms are relatively large (the median number of workers is 151, while its average is 5868 because of its thick-tailed distribution) and often foreign owned (the share of foreign-owned firms is 32%). The selection of the sample may be justified to some extent because we aim to examine the effect of the characteristics of firms' links with global supply chains on their resilience and robustness. If most respondent firms were domestically confined small and medium-sized enterprises, the variation in their international diversity of supply chain partners would be quite limited, and thus, we could not estimate the effect of diversity. However, it should also be emphasised that the results from our analysis should be applied mainly to large or multinational firms.

Moreover, our results may be biased because of the sample selection. For example, if firms that did not diversify their supply chains internationally and thus were heavily affected by the pandemic were less likely to be included in our sample because they were too busy recovering from the pandemic, the correlation between the level of international diversity of suppliers and resilience in our sample would be weaker than the correlation in the population. In other words, the effect of international diversity on resilience estimated in this study would be underestimated.[3] Similarly, if firms that diversified their supply chains and thus were not greatly affected by the pandemic were less likely to be included in our

[3]More precisely, this case occurs if the error terms in the equations for firms' resilience ($y_1 = X'\beta + \varepsilon_1$) and for their selection in the sample ($y_2 = X'\delta + \varepsilon_2$: firms are observed if $y_2 > 0$) are positively correlated. Then, firms' expected performance given that they are in the sample is determined by observed covariates including the diversity measure and the inverse Mills ratio, of which the coefficient is the covariance of the two error terms, ρ, times the variance of the former error, σ_2: $E(y_1|y_2 > 0) = X'\beta + \rho\sigma_2\phi(X'\beta)/\Phi(X'\beta)$ (Wooldridge, 2010). Because the inverse Mills ratio is negatively correlated with the diversity measure in this case and ρ is positive, the error term using the biased sample is negatively correlated with the diversity measure. Therefore, the estimate of the effect of diversity on resilience is underestimated.

sample because they were busy enjoying the economic benefits of the pandemic, the effect of diversity would also be underestimated.[4]

Second, our estimation results may be biased upwards because of endogeneity mostly stemming from omitted variables, although we try to avoid this bias by including a number of controls and dummy variables (Section 3.2). Most notably, the robustness and resilience of supply chains can be determined by the managerial skills of each firm, which are unobservable in our data. If the level of managerial skills and the degree of international diversity of supply chain partners are positively correlated, the effect of diversity is overestimated in our analysis. Another source of omitted variable bias in the link-level analysis is unobserved measures of tie strength. We experimented with other measures of homophily, such as measures based on firm size and industry, and found that their effect on resilience is either insignificant or not robust across different estimations and thus did not use them in the estimations of this study. However, there may be other unobserved measures of tie strength, such as similarity in managers' education level and age, their membership in the same organisation and tie duration. If these measures affect tie robustness and are positively correlated with the observed measures of tie strength, that is, the measure of homophily in terms of the country of origin and the ownership relationship, the effect of each of the latter will be overestimated.

To check whether our results are greatly biased by endogeneity, we conduct placebo tests in the firm-level analysis by using each of the measures of robustness, *ROBc* and *ROBs*, as the dependent variable in Equation (2), instead of the resilience measures. If endogeneity bias affects our estimations of the effect on firm resilience, the estimated effect on robustness should also be biased because unobserved managerial skills may be similarly correlated with firms' resilience and robustness. However, as shown later in Section 5.2, the estimated correlation between diversity and robustness is found to be insignificant in any placebo test. Therefore, although there is a possibility of endogeneity bias in our estimations, we conclude that the size of the bias may not be substantial.

5 | RESULTS

5.1 | Link-level analysis on robustness

We start with the analysis at the level of supply chain links, as described in Section 3.1. The estimation of Equation (1) using the data for links with customers generates the following results, as shown in column (1) of Table 7.

First, *HOM_FDIc*, the dummy variable for the equivalence of the home country of a foreign-owned respondent firm and the country of its customer, is also negatively correlated with *SHRINKc* at the 5% level. This result supports hypothesis 2 in Section 2.2 and indicates that homophily in geography leads to robustness of supply chain links with customers. The size of the coefficient suggests that the probability of a shrinking transaction volume between a homophilous link is 8.4 percentage points lower than the probability for a heterophilous link. Because the average probability of shrinking transactions is 31% (Table 6), the effect of homophily on the robustness of supply chain links is substantial in size. We further investigate whether the effect of *HOM_FDIc* differs across home countries by using interaction terms between *HOM_FDIc* and home country dummies. The results, not shown here for brevity, indicate that none of the coefficients of any of the interaction terms are significantly different from 0, implying no variation across home countries.

Second, *OWNc* is positively and significantly correlated with *SHRINKc*, indicating that transactions between a firm and its customer were more likely to shrink due to COVID-19 when the customer owns the firm. In addition, *OWNEDc* is not significantly correlated with the dependent variable. These findings

[4]Using Monte Carlo simulations, we confirm that the sample selection results in underestimation of the effect in both cases.

TABLE 7 Link-level analysis

Independent variable	(1) SHRINKc	(2) SHRINKc		(3) SHRINKs	(4) SHRINKs
HOM_FDIc	−0.0836**	−0.0747**	*HOM_FDIs*	−0.138***	−0.136***
	(0.0344)	(0.0345)		(0.0429)	(0.0432)
OWNc	0.160***	0.209***	*OWNs*	0.122***	0.121*
	(0.0398)	(0.0542)		(0.0435)	(0.0671)
OWNEDc	−0.0292	−0.0448	*OWNEDs*	0.0302	0.0422
	(0.0337)	(0.0382)		(0.0468)	(0.0701)
OWNc × *FDI*		−0.133**	*OWNs* × *FDI*		−0.00301
		(0.0667)			(0.0869)
OWNEDc × *FDI*		0.0328	*OWNEDs* × *FDI*		−0.0327
		(0.0613)			(0.0828)
HHIp	−0.0623*	−0.0615*	*HHIp*	−0.0710	−0.0700
	(0.0373)	(0.0372)		(0.0444)	(0.0446)
ln*L*	−0.0127***	−0.0125***	ln*L*	−0.00152	−0.00149
	(0.00418)	(0.00419)		(0.00541)	(0.00544)
ln*AGE*	0.0289***	0.0288***	ln*AGE*	0.0327**	0.0328**
	(0.0105)	(0.0105)		(0.0158)	(0.0159)
Lc_medium	0.00927	0.0105	*Ls_medium*	−0.0927***	−0.0923***
	(0.0395)	(0.0398)		(0.0318)	(0.0321)
Lc_large	−0.0459	−0.0440	*Ls_large*	−0.125***	−0.124***
	(0.0316)	(0.0314)		(0.0305)	(0.0306)
Country × Industry FE	Yes	Yes	Country × industry FE	Yes	Yes
Customer's country ×Industry FE	Yes	Yes	Supplier's country ×industry FE	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Home country FE (if foreign owned)	Yes	Yes
Controls	Yes	Yes	Controls	Yes	Yes
Observations	4269	4269	Observations	3931	3931
R squared	0.111	0.112	R squared	0.117	0.117

Note: Robust standard errors at the country–industry–partner's country level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

do not support our prediction in hypothesis 1 in Section 2.2 that supply chain ties additionally associated with ownership relationships are strong and thus robust to economic shocks. In particular, the finding on *OWNc* implies that a supplier tends to decrease its sales to its customer that owns the supplier more than to other arm's-length customers without any ownership relationship. However, it should be noted that this finding does not fully contradict our conceptual considerations or existing empirical findings described in Section 2.3. The coexistence of supply chain and ownership relationships may result in input specificity that causes vulnerability in the wake of economic shocks (Barrot & Sauvagnat, 2016) and dense networks that facilitate the circulation of shocks among partners (Inoue & Todo, 2019a, 2019b). Boehm et al. (2019) and Kashiwagi et al. (2021) also showed the propagation of economic shocks through supply chains associated with ownership relationships. Another possible interpretation of this finding is that the owner firm benefits more in the long run from prioritising arm's-length transactions than from prioritising intra-firm transactions because arm's-length transactions cannot recover easily once destroyed by a shock. In other words, firms can modify the volume of intra-firm transactions more flexibly than that of arm's-length transactions because of the smaller short-run adjustment costs of the former. The importance of flexibility in supply chain resilience is emphasised in the literature (Ali et al., 2017; Azadeh et al., 2014; Crum et al., 2011; Gunasekaran et al., 2015; Pereira et al., 2014).

We further check heterogeneity in the effect of ownership by incorporating interaction terms between the dummies for ownership relationships and the dummy for foreign ownership of the respondent firm. The results presented in column (2) of Table 7 indicate that the coefficient of the interaction term between the dummy for the customer owning its supplier (*OWNc*) and the foreign ownership dummy (*FDI*) is negative and significant at the 5% level. Moreover, the hypothesis that the sum of the coefficients of *OWNc* and *OWNc*FDI* is 0 cannot be rejected. These results suggest that foreign-owned firms can mitigate the negative effect of strong ties on robustness found in column (1) of Table 7.

Third, *HHIp*, the inverse measure of international diversity of production sites of the respondent firm, is negatively correlated with *SHRINKc* at the 10% level (column (1) of Table 7). As hypothesis 3 in Section 2.4 explained, this result weakly indicates that when a firm's production sites were diversified across countries, the firm was more likely to be damaged by multi-country economic shocks due to COVID-19 but could not substitute other undamaged sites for the damaged sites and thus reduced production and its transactions with its customer.

Columns (3) and (4) in Table 7 show corresponding results using the data for links between the respondent firms and their suppliers. The results are mostly similar to those using the data for links with customers: The effect of homophily in location (*HOM_FDIs*) on robustness is negative, and the effect of ownership relationships (*OWNs*) is positive. However, there are a few differences. First, the interaction term between the dummies for ownership relationship and for foreign ownership is not significantly correlated with the change in transaction volumes, suggesting no difference between domestic and foreign-owned firms in the effect of the supplier's ownership of its customer. Second, the effect of *HHIp*, the inverse level of diversity of production sites of the respondent firm, is negative but not significant. Combined with the previous finding that the effect of *HHIp* is significant only at the 10% level, it is not clear whether international diversity in the production sites of firms deteriorates the robustness of their own production.

Finally, we touch on some interesting results on the control variables. ln*L* shows a negative and significant correlation with *SHRINKc*, while ln*AGE* shows a positive and significant correlation in columns (1) and (2) of Table 7. ln*AGE* is also positively correlated with *SHRINKs* in columns (3) and (4) of Table 7, whereas the coefficients of *Ls_medium* and *Ls_large* are negative and significant. In other words, the transaction between a supplier and its customer was less likely to shrink because of COVID-19, or more likely to be robust, when the two firms are younger and when the supplier is larger.

In addition, we check differences in the effect on transaction volumes across the home countries of foreign-owned firms. We find that Japanese-affiliated suppliers in the ASEAN and India were less likely to reduce the transaction volume with their customers by 15–16 percentage points than other suppliers, including domestically owned and other foreign-owned suppliers. In contrast, the transactions of foreign-owned firms from any other country were affected as much as those of domestically owned firms. The results imply the relative robustness of links with Japanese-owned firms in Asia.

5.2 | Firm-level analysis on resilience and performance

Now, we turn to the firm-level analysis to examine how the resilience of firms' supply chains is determined. We first investigate how the resilience of links with customers is determined by the geographic

TABLE 8 Firm-level analysis focusing on relationships with customers

Independent variable	(1)	(2)	(3)	(4)
	Dependent variable			
	RESc		*ROBc*	
DIVERSc	0.0235***		−0.000924	
	(0.00822)		(0.0128)	
HHIc		−0.0704**		−0.0570
		(0.0344)		(0.0594)
HHIp	0.0707*	0.0804**	0.0324	0.0778
	(0.0355)	(0.0353)	(0.0599)	(0.0748)
ln*L*	0.00160	0.00133	0.0152***	0.0161***
	(0.00457)	(0.00458)	(0.00568)	(0.00566)
ln*AGE*	0.0169*	0.0163*	−0.0426**	−0.0424**
	(0.00933)	(0.00942)	(0.0173)	(0.0176)
Country × Industry FE	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	1416	1416	1416	1416
R squared	0.080	0.083	0.093	0.097

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

diversity of customers and other firm attributes and show the results in Table 8. In columns (1) and (2), the dependent variable is *RESc*, the dummy variable for the coexistence of a decrease in the transaction volume with a customer and an increase in the transaction volume with another that indicates the resilience of links with customers. In column (1), the key independent variable is *DIVERSc*, the number of countries where the top three customers are located, whereas in column (2), it is *HHIc*, the HHI of the share of sales by country. *DIVERSc* is positively correlated with *RESc*, while *HHIc* is negatively correlated. Because *HHIc* is an inverse measure of diversity, both results indicate that geographic diversity of customers led to resilience of links with customers when firms were faced with supply chain disruptions due to the COVID-19 pandemic. Because the standard deviations of *DIVERSc* and *HHIc* are 0.82 and 0.40 (Table 5), an increase in the diversity measures by one standard deviation results in an increase in the resilience dummy, *RESc*, by 0.02–0.03. Because the average of the resilience dummy is 0.091 (Table 5), the effect of diversity is substantial. In addition, *HHIp*, the HHI of the share of production by country, is positively and significantly correlated with the resilience measures. This finding implies that geographic diversity in the production sites of a particular firm deteriorates the resilience of its links with customers, possibly because under the multi-country economic shocks from the global spread of COVID-19, several production sites may have been affected and thus substitution across production sites may have been difficult. However, as in Table 7, the effect of *HHIp* is significant only at the 10% level, and thus, the evidence is weak.

In Table 9, we focus on links with suppliers and conduct the corresponding analysis. In column (1), we find a positive effect of the measure of diversity of suppliers, *DIVERSs*, on the resilience of links with suppliers. Although the effect of the reverse diversity measure, *HHIs*, is not significant in column (2), our findings suggest that firms that diversify suppliers across countries, when facing a disruption of supplies from a supplier, can flexibly procure supplies from another supplier.

TABLE 9 Firm-level analysis focusing on relationships with suppliers

Independent variable	(1)	(2)	(3)	(4)
	Dependent variable			
	RESs		ROBs	
DIVERSs	0.0423***		−0.0114	
	(0.0109)		(0.0179)	
HHIs		−0.0352		0.0318
		(0.0391)		(0.0619)
HHIp	−0.00607	−0.0264	0.0320	0.0268
	(0.0364)	(0.0437)	(0.0554)	(0.0659)
ln*L*	0.00371	0.00378	0.00979	0.00967
	(0.00284)	(0.00283)	(0.00659)	(0.00657)
ln*AGE*	0.0136	0.0139	−0.0484**	−0.0475**
	(0.00857)	(0.00861)	(0.0186)	(0.0182)
Country × Industry FE	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	1316	1316	1316	1316
R squared	0.092	0.079	0.098	0.099

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

Furthermore, we experiment with placebo tests where the measures of the *robustness* of supply chain links, that is, *ROBc* and *ROBs*, rather than the *resilience* measures, are used as the dependent variable. As explained in detail in Section 4.3, the robustness measures would be correlated with the measures of geographic diversity of suppliers or customers if managerial skills that are omitted in our analysis were correlated with the robustness of firms. The results from the placebo tests in columns (3) and (4) of Tables 8 and 9 indicate that none of the (reverse) diversity measures is significantly correlated with the robustness measures. These placebo tests highlight the importance of the geographic diversity of customers and suppliers in the resilience of supply chain links, that is, the substitutability of partners after economic shocks, but not in their robustness. The results also suggest that endogeneity bias from omitted variables may not be substantial in our estimations on resilience.

In columns (3) and (4) of Tables 8 and 9, it is notable that *HHIp*, the measure of the geographic concentration of production sites, is not significantly correlated with any robustness measure. This finding contrasts with the negative correlation of *HHIp* with *SHRINKc* in columns (1) and (2) of Table 7, which presents a positive effect of geographic concentration on robustness at the link level. Considering further that the correlation in Table 7 is significant at only the 10% level, the positive effect of the geographic concentration of production sites on the robustness of a firm's supply chains is not robust or at best weak.

As we mentioned in Section 4.2, a shortcoming of the use of the resilience measures in linear probability models [columns (1) and (2) of Tables 8 and 9] is that the resilience measures are zero for two different types of firms: those that did not reduce their transactions with any of the three customers or suppliers (i.e. robust firms) and those that reduced their transactions with all of them. Therefore, as a robustness check, we estimate multinomial logit models where the dependent variable is a categorical variable (*RESROBc* or *RESROBs*) that is 1 if the respondent firm is resilient, 2 if it is robust and 0

TABLE 10 Firm-level analysis focusing on relationships with customers (multinomial logit estimation)

	(1)		(2)	
	RESc	**ROBc**	**RESc**	**ROBc**
DIVERSc	0.330***	0.0457		
	(0.101)	(0.0616)		
HHIc			−1.134***	−0.462*
			(0.429)	(0.280)
HHIp	1.286**	0.403	1.561***	0.656**
	(0.575)	(0.275)	(0.528)	(0.322)
ln*L*	0.0634	0.0839***	0.0632	0.0869***
	(0.0575)	(0.0251)	(0.0572)	(0.0243)
ln*AGE*	0.129	−0.143**	0.125	−0.146**
	(0.116)	(0.0718)	(0.117)	(0.0736)
Country FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	1416	1416	1416	1416

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

otherwise. Setting the value of zero as the base case, we show the estimation results for relationships with customers in Table 10 and those for relationships with suppliers in Table 11. These results are quite consistent with those in Tables 8 and 9 from the separate estimations for resilience and robustness: the geographic diversity of supply chain partners has a positive effect on resilience but not on robustness. One difference is that the effect of *HHIc*, the inverse measure of diversity, on robustness is negative and significant (column 2: *ROBc* in Table 10). However, because the significance level is only 10% and the effect on robustness is substantially smaller than the effect on resilience, we maintain our previous conclusion that endogeneity bias is limited.

We further investigate whether firm performance is correlated with the robustness and resilience of supply chains. For this purpose, we run OLS regressions of sales in 2020, profits in 2020, exports in 2020, predicted profits in 2021 and predicted employment in 2021 on the measures of the robustness and the resilience of links with customers or suppliers at the firm level and other controls. In this analysis, we use the robustness and the resilience of links with customers and suppliers in separate regressions to avoid multicollinearity between these variables. The dependent variables are categorical variables that take a value of 1, 2, 3, 4 or 5 if the change rate in the firm performance from the previous year is −50% or less, −1% to −49%, 0%, 1% to 49% or 50% or more respectively.

The results are shown in Table 12. The upper and lower rows present the results from using the measures of the robustness and resilience of links with customers and suppliers respectively. Throughout the estimations, the robustness of links with customers and suppliers is positively and significantly correlated with firm performance, indicating the importance of maintaining links with customers. The resilience of links with customers and suppliers is correlated with predicted firm performance but not particularly strongly correlated with current performance.

Finally, we point to the effect of the size and age of firms on their robustness, resilience and performance. The results in Tables 8–10 indicate that larger and younger firms were more likely to

TABLE 11 Firm-level analysis focusing on relationships with suppliers (multinomial logit estimation)

	(1)		(2)	
	RESs	ROBs	RESs	ROBs
DIVERSs	0.654***	0.0384		
	(0.163)	(0.0883)		
HHIs			−0.523	0.186
			(0.585)	(0.313)
HHIp	−0.00765	0.161	−0.384	0.0233
	(0.488)	(0.244)	(0.596)	(0.295)
ln*L*	0.0671	0.0599**	0.0674*	0.0603**
	(0.0442)	(0.0301)	(0.0392)	(0.0296)
ln*AGE*	0.133	−0.163*	0.145	−0.159*
	(0.156)	(0.0854)	(0.149)	(0.0842)
Country FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	1416	1416	1416	1416

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

be robust, resilient and high performing during the COVID-19 pandemic. Although this conclusion does not always hold and depends on specifications, it is consistent with the results from the link-level analysis presented in Table 7. While it is intuitively understandable that larger firms tend to be robust, resilient and high performing, it is notable that younger firms tend to be so. This is possibly because our sample firms are in the ASEAN and India, emerging economies where traditional and inefficient firms are being replaced by young and active firms.

6 | DISCUSSION AND CONCLUSIONS

This article examines what determined the robustness and resilience of supply chain links, that is, the ability to maintaining links and recovering disrupted links by substitution, respectively, when firms faced economic shocks due to the COVID-19 pandemic, focusing on the role of the characteristics of firms' supply chains. The empirical results and implications obtained from the results can be summarised as follows.

First, homophily in geography is often associated with robustness of supply chain links, most likely because of the strength of homophilous ties, as suggested in the literature (Louch, 2000; Ruef et al., 2003). Specifically, if a foreign-owned firm has a supply chain link with a firm located in the same country as the foreign-owned firm's home country, the link is quite robust. Furthermore, the robustness of supply chains is found to be a key factor of higher firm performance in the middle of economic shocks, in both the short and the long run.

Second, when firms are linked through both supply chains and ownership relationships, the transaction volume between them tends to decline more than when they are linked through only supply chains. This negative effect of ownership relationships on the robustness of links is prominent for

TABLE 12 Firm-level analysis of effects of robustness and resilience of supply chains

Independent variable	(1) Dependent variable: Sales in 2020	(2) Profits in 2020	(3) Exports in 2020	(4) Predicted profits in 2021	(5) Predicted employment in 2021
ROBc	0.465***	0.333***	0.144**	0.404***	0.189***
	(0.0733)	(0.0601)	(0.0568)	(0.0569)	(0.0299)
RESc	0.116	0.244**	0.122	0.396***	0.108*
	(0.111)	(0.104)	(0.0988)	(0.0755)	(0.0582)
ln*L*	0.0347**	0.0402*	0.0266*	0.0208**	0.0131*
	(0.0148)	(0.0219)	(0.0146)	(0.0101)	(0.00729)
ln*AGE*	−0.141***	−0.182***	−0.0948***	−0.0683***	−0.0723***
	(0.0372)	(0.0363)	(0.0279)	(0.0217)	(0.0148)
Observations	1372	1233	1390	1422	1432
R squared	0.144	0.116	0.096	0.157	0.129
ROBs	0.360***	0.269**	0.113*	0.320***	0.212***
	(0.0841)	(0.102)	(0.0635)	(0.0516)	(0.0433)
RESs	−0.104	0.0530	−0.126	0.212**	0.0959
	(0.168)	(0.175)	(0.117)	(0.0859)	(0.0630)
ln*L*	0.0469***	0.0423**	0.0184	0.0186**	0.0158**
	(0.0143)	(0.0202)	(0.0152)	(0.00844)	(0.00783)
ln*AGE*	−0.155***	−0.167***	−0.0854***	−0.0606***	−0.0729***
	(0.0359)	(0.0393)	(0.0298)	(0.0210)	(0.0152)
Observations	1222	1093	1237	1267	1274
R squared	0.165	0.131	0.112	0.159	0.154
Country × Industry FE	Yes	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

domestically owned firms but not for foreign-owned firms. There are several possible reasons for the negative effect of strong supply chain links. First, strong links are often associated with specific inputs and thus vulnerability in the wake of shocks. Second, strong links are often associated with clusters where firms are densely connected with each other, resulting in circulation of shocks in the cluster. Finally, firms may try to maintain arm's-length transactions more than intra-firm transactions because the former may not be recovered easily once lost due to economic shocks. Combined with the first finding, this implies that strong supply chain links are not necessarily robust.

Third, the geographic diversity of customers and suppliers creates resilience of supply chains. When the demand or supply from a partner of a firm is disrupted because of economic shocks, the firm can mitigate the damage from the disruption by replacing the affected partner with another if the firm's supply chains are well diversified across countries. The resilience of supply chains, particularly those with customers, further results in higher performance in the long run.

Finally, the geographic diversity of production sites is found to be significantly negatively correlated with the robustness and resilience of supply chain links in some specifications at the 10% level, although the correlation is not statistically significant in others. The lack of robustness and weak significance of the negative effect of the geographic diversity of production sites possibly arises due to the following two contrasting forces. On the one hand, when the production sites of a firm are geographically diversified and economic shocks spread across countries, the probability that some of its production sites are affected by a shock increases. On the other hand, because the probability that some others are not affected is also higher in the case of geographic diversity than otherwise, the firm may mitigate the economic shock by substituting active sites for affected sites. Because of the two opposing forces, the overall effect of the geographic diversity of production on the robustness and resilience of supply chains is unclear.

These two forces related to the geographic diversification of production sites can also be considered in regard to the diversification of supply chain partners. Our results on the effect of supply chain diversity [columns (1)–(2) of Tables 8 and 9], which are more robust and significant than those on the effect of production diversity, suggest that the positive effect of supply chain diversity through increasing the substitutability of customers and suppliers surpasses its negative effect through increasing the risk of supply chain disruptions. Therefore, to be robust and resilient to economic shocks, firms are suggested to diversify their supply chain partners geographically, including through further globalisation of their supply chains.

Two caveats to this article should be pointed out, as we explained in detail in Section 4.3. First, our sample is not obtained from random sampling, and thus large or foreign-owned firms are overweighted in our sample. Accordingly, our results may be biased because of sample selection. However, this sampling strategy may be justified because our focus is on global supply chains. In addition, it should be emphasised that our data are quite unique in that they contain information about changes in transactions in each supply chain link, not only changes in firm-level performance or country–industry-level trade. Second, although our key independent variables, such as the measures of homophily between firm pairs and the geographic diversity of customers and suppliers, are predetermined, they would still be correlated with the error term through related but unobservable effects. To alleviate endogeneity bias because of omitted variables, we include as many control variables as possible, including a full set of dummy variables. We also check the presence of endogeneity bias using placebo tests (Section 4.3) and find that bias may be limited at least in the firm-level analysis (Section 5.2). However, we should admit that endogeneity bias may remain in our estimations. We leave these issues for future research.

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DATA AVAILABILITY STATEMENT

When ERIA collected the data used in this study, ERIA assured respondent firms that data are used for only ERIA research projects. Therefore, the data cannot be shared outside ERIA.

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APPENDIX A

TABLE A1 Link-level analysis

Independent variable	(1) SHRINKc	(2) SHRINKc		(3) SHRINKs	(4) SHRINKs
HOM_FDIc	−0.0904***	−0.0786**	*HOM_FDIs*	−0.152***	−0.148***
	(0.0344)	(0.0345)		(0.0438)	(0.0444)
OWNc	0.145***	0.207***	*OWNs*	0.114***	0.119*
	(0.0408)	(0.0549)		(0.0439)	(0.0688)
OWNEDc	−0.0318	−0.0521	*OWNEDs*	0.00484	0.0227
	(0.0323)	(0.0374)		(0.0473)	(0.0720)
OWNc × FDI		−0.168**	*OWNs × FDI*		−0.0223
		(0.0673)			(0.0889)
OWNEDc × FDI		0.0375	*OWNEDs × FDI*		−0.0570
		(0.0638)			(0.0856)
HHIp	−0.0722*	−0.0720*	*HHIp*	−0.0959**	−0.0943**
	(0.0405)	(0.0404)		(0.0452)	(0.0454)
ln*L*	−0.0150***	−0.0146***	ln*L*	0.000878	0.000840
	(0.00528)	(0.00530)		(0.00729)	(0.00736)
ln*AGE*	0.0268**	0.0265**	ln*AGE*	0.0284*	0.0284*
	(0.0106)	(0.0106)		(0.0166)	(0.0167)
Lc_medium	−0.000457	0.00122	*Ls_medium*	−0.102***	−0.101***
	(0.0398)	(0.0401)		(0.0325)	(0.0328)
Lc_large	−0.0395	−0.0373	*Ls_large*	−0.136***	−0.134***
	(0.0310)	(0.0308)		(0.0321)	(0.0322)
Country × Industry FE	Yes	Yes	Country × industry FE	Yes	Yes

(Continues)

TABLE A1 (Continued)

Independent variable	(1) SHRINKc	(2) SHRINKc		(3) SHRINKs	(4) SHRINKs
Customer's country × Industry FE	Yes	Yes	Supplier's country × industry FE	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Home country FE (if foreign owned)	Yes	Yes
Controls	Yes	Yes	Controls	Yes	Yes
Observations	3993	3993	Observations	3651	3651
R squared	0.117	0.125	*R* squared	0.125	0.125

Note: Robust standard errors at the country–industry-partner's country level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

TABLE A2 Firm-level analysis focusing on relationships with customers

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable					
Independent variable	**RESc**		**EXPANDc**		**ROBc**	
DIVERSc	0.0241***		0.0643***		−0.00321	
	(0.00836)		(0.0222)		(0.0138)	
HHIc		−0.0705*		−0.172*		−0.0503
		(0.0383)		(0.0905)		(0.0641)
HHIp	0.0822**	0.0902**	0.173**	0.190**	0.0426	0.0841
	(0.0404)	(0.0394)	(0.0773)	(0.0765)	(0.0658)	(0.0809)
ln*L*	−0.000495	−0.000815	0.00740	0.00534	0.0155**	0.0158**
	(0.00486)	(0.00477)	(0.00973)	(0.00965)	(0.00610)	(0.00611)
ln*AGE*	0.0156	0.0148	0.0140	0.0161	−0.0398**	−0.0397**
	(0.0105)	(0.0107)	(0.0216)	(0.0218)	(0.0184)	(0.0187)
Country × industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1326	1326	625	625	1326	1326
R squared	0.082	0.085	0.181	0.182	0.095	0.098

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

TABLE A3 Firm-level analysis focusing on relationships with suppliers

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable					
Independent variable	**RESs**		**EXPANDs**		**ROBs**	
DIVERSs	0.0383***		0.0776***		−0.00713	
	(0.0110)		(0.0264)		(0.0197)	
HHIs		−0.0134		−0.00577		0.00778
		(0.0456)		(0.109)		(0.0659)
HHIp	−0.0108	−0.0380	0.00209	−0.0794	0.0689	0.0742
	(0.0393)	(0.0486)	(0.0871)	(0.106)	(0.0597)	(0.0718)
ln*L*	0.00537	0.00536	0.0189**	0.0201***	0.0110	0.0108
	(0.00393)	(0.00397)	(0.00714)	(0.00725)	(0.00846)	(0.00860)
ln*AGE*	0.0110	0.0113	0.0149	0.0180	−0.0423**	−0.0413**
	(0.00913)	(0.00912)	(0.0208)	(0.0213)	(0.0194)	(0.0192)
Country × Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1225	1225	562	562	1225	1225
R squared	0.089	0.076	0.187	0.166	0.100	0.101

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.

TABLE A4 Firm-level analysis of effects of robustness and resilience of supply chains

	(1)	(2)	(3)	(4)	(5)
	Dependent variable				
Independent variable	**Sales in 2020**	**Profits in 2020**	**Exports in 2020**	**Predicted profits in 2021**	**Predicted employment in 2021**
ROBc	0.493***	0.300***	0.255***	0.299***	0.135***
	(0.102)	(0.109)	(0.0902)	(0.0654)	(0.0437)
RESc	0.177	0.142	0.174	0.373***	0.111*
	(0.136)	(0.147)	(0.118)	(0.0847)	(0.0566)
ROBs	0.0705	0.0889	−0.0218	0.143**	0.124***
	(0.102)	(0.109)	(0.0893)	(0.0648)	(0.0433)
RESs	−0.273*	−0.0754	−0.212	0.0573	0.0394
	(0.147)	(0.160)	(0.132)	(0.0932)	(0.0623)
ln*L*	0.0369*	0.0382*	0.00708	0.0114	0.0140
	(0.0203)	(0.0218)	(0.0178)	(0.0129)	(0.00861)
ln*AGE*	−0.158***	−0.190***	−0.0857**	−0.0724***	−0.0719***
	(0.0405)	(0.0430)	(0.0347)	(0.0253)	(0.0169)
Country × Industry FE	Yes	Yes	Yes	Yes	Yes
Home country FE (if foreign owned)	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Observations	1138	1016	1153	1184	1189
R squared	0.179	0.140	0.116	0.172	0.152

Note: Robust standard errors at the country–industry level are in parentheses. ***$p < .01$, **$p < .05$, *$p < .1$.