

Catastrophic supply chain disruptions and supply network changes: A study of the 2011 Japanese earthquake from a supply network complexity view

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Abstract

Catastrophic supply chain disruptions can significantly damage the operational and financial performance of firms. While a growing body of literature on supply network structures has studied what influences supply networks' vulnerability to supply chain disruptions and capability to recover from the disruptions, it remains unclear how supply network structures change after major supply chain disruptions. Using a natural experiment approach, this study investigates how firms' ego supply network structures change after experiencing the catastrophic supply chain disruptions caused by the 2011 Tōhoku earthquake and tsunami in Japan. The results of the analysis suggest that compared to unaffected firms, firms affected by the disruptions have lower levels of supply network complexity after the disruptions. This study contributes to the literature on supply network structures and supply chain resilience by providing empirical evidence of structural changes in supply networks after catastrophic supply chain disruptions. The paper concludes with a reflection on why these changes might be occurring and alerts firms to the challenges of managing complexity in their supply networks.

KEYWORDS

supply networks, network change, supply chain disruption, natural disaster, supply chain resilience

1. INTRODUCTION

Supply chain disruptions can significantly damage the operational and financial performance of firms (Hendricks & Singhal, 2005; Wagner & Bode, 2008). Building supply chain resilience helps firms mitigate the impact of disruptions more effectively and recover more quickly. Supply chain resilience is the sum of two opposing forces: the vulnerability of the supply chain to shocks, and the capability to respond to and recover from these shocks. Significant research has been carried out to understand what drives the vulnerability (e.g., Bode & Wagner, 2015; Craighead et al., 2007) and the capabilities that supply chains need to develop to become resilient (e.g., Chopra & Sodhi, 2014; Pettit et al., 2013; Sheffi & Rice, 2005).

The growing body of work on supply network structures offers important contributions to both the vulnerability and capability aspects of supply chain resilience. Research on supply network structures goes beyond looking at the cumulative impact of dyadic relationships and focuses on the opportunities and challenges that arise from the complex inter-relationships in the network (Choi & Kim, 2008). Past supply network research has investigated how the structural characteristics of supply networks affect firm performance, including innovation (Bellamy et al., 2014) or financial performance (Lu & Shang, 2017). Within the context of supply chain disruption and resilience, network-level studies have adopted a complexity perspective in explaining why supply chains are vulnerable to external shocks when the network is large and there are many dyadic relationships among the network partners (Bode & Wagner, 2015; Choi & Krause, 2006; Scheibe & Blackhurst, 2018).

Although there has been significant research on the impact of supply network

complexity on supply chain resilience and disruption recovery, what still remains unclear is the impact of disruptions, particularly catastrophic disruptions, on supply network structures. If supply network complexity exposes firms to higher supply chain risks, the firms that suffered from major disruptions may attempt to reduce the overall levels of complexity to make their supply chains more resilient by adjusting their supply network structures. To our knowledge, however, no research has focused on the structural changes in supply networks after significant supply chain disruptions. In fact, there is relatively little work on the transformation of supply networks in general. With the exception of Park et al.'s study (2018) on the evolution of supply chain alliance networks, few studies have explored empirically how supply network structures change and what drives those changes.

In short, there are two gaps in the research on the relationship between supply network structures and supply chain resilience. First, there is not enough understanding of how disruptions shape supply network structures. Second, there is very limited work on how and why supply network structures change. Building on the literature on supply chain risk and resilience, supply network complexity, and network structural changes, we aim to understand how supply network structures—specifically supply network complexity—change after firms experience catastrophic supply chain disruptions. We adopt a natural experiment approach utilizing the difference-in-differences analysis; and take the 2011 Tōhoku earthquake and tsunami (henceforth *the earthquake*) as the research setting for investigating supply network structural changes of the firms affected by catastrophic supply chain disruptions. In line with prior research on supply network complexity and supply network structures, we capture the supply network complexity using the measures of degree centrality and

ego network density.

The results from our analysis suggest that firms that have faced catastrophic disruptions followed by an event such as *the earthquake* demonstrate reduced levels of supply network complexity, measured by in-degree centrality, out-degree centrality, and ego network density, compared to those that were not affected by it. We reflect on why this might be happening as well as possible consequences of this shift. While research on complexity suggests that this should be seen as a correction to the destructive effects of supply network complexity, the new status quo is likely to bring with it its own risks.

Our study contributes to the fast-growing literature on supply network structures by empirically investigating structural changes resulting from catastrophic supply chain disruptions caused by a major natural disaster. Moreover, we contribute to the supply chain resilience literature by focusing on how the vulnerability exposed by catastrophic supply chain disruptions brings subsequent structural changes in supply networks. We provide empirical evidence that firms experience adjustments in their supply network structures; some potentially driven by them, and others initiated by the supply chain partners. Overall, compared to non-affected firms, the firms that experienced major disruptions in their supply chains have reduced overall levels of supply network complexity. We go beyond the extant studies that report on the negative impact of supply network complexity on supply chain resilience and reveal how firms' supply chain complexity is altered after suffering from catastrophic supply chain disruptions.

2. THEORETICAL BACKGROUND

2.1. Supply chain resilience from a supply network complexity perspective

A supply chain disruption refers to an unanticipated event that disrupts the normal flow of goods within a supply chain, thereby exposing the firms within the supply chain to operational and financial risks (Craighead et al., 2007). The damaging nature of supply chain disruptions has motivated researchers to investigate (1) the causes of supply chain disruptions (e.g., Blackhurst et al., 2008; Bode & Wagner, 2015; Craighead et al., 2007; Svensson, 2000), (2) their operational and financial impact (e.g., Hendricks & Singhal, 2003; 2005a; 2005b), and (3) how a firm can build supply chain resilience, defined as the capability to withstand and recover from supply chain disruptions (e.g., Brandon-Jones et al., 2014; Kleindorfer & Saad, 2005; Wagner & Bode, 2006).

The supply chain resilience of a firm is the sum total of its vulnerabilities, which are the basic elements that make it sensitive to disruptions, and the capabilities that help it to overcome them (Pettit et al., 2010, 2013; Sheffi & Rice, 2005). The scale of its supply network can be a significant driver of a firm's vulnerability (Pettit et al., 2013). Moreover, the vulnerability of the individual companies in the supply network have a knock-on effect in that "the failure of any one element in it could cause the whole network to fail" (Rice & Caniato, 2003: p. 22).

More recent research has aimed at pinpointing what exactly about the network structure creates this vulnerability and thereby reduces resilience. In that regard, supply network complexity has been an influential and informative concept. The "complexity perspective" of supply chain resilience proposes that a firm having an excessive number of ties with other companies and the inter-relationships between these companies could potentially both become a gateway for the propagation of

disruptions and hinder an effective disruption response (Bode & Wagner, 2015; Choi & Krause, 2006; Chowdhury & Quaddus, 2017; Craighead et al., 2007; Kim et al., 2015; Scheibe & Blackhurst, 2018). Influential studies based on the complexity perspective (e.g., Choi & Krause, 2006; Kim et al., 2015) have used the NK model (Kauffman & Levin, 1987; Levinthal, 1997) where N represents the number of suppliers of a focal firm and K represents the inter-relationships among them. These correspond to the degree centrality and density metrics in network analysis (Kim et al., 2011).

Degree centrality captures the importance of an individual firm in the network (Borgatti & Li, 2009; Kim et al., 2011). The more central a firm is the better it has access to resources (Lu & Shang, 2017), yet this advantage also comes at a cost: Past studies have suggested that the more central a firm is, the more likely it is to experience a supplier induced disruption (Bode & Wagner, 2015; Perrow, 1984). Moreover, the number of network ties impacts the extent of coordination efforts of the focal firm (Kim et al., 2011). It is positively related to the level of transaction intensity a focal firm faces (Bode & Wagner, 2015; Powell et al., 2005) and can result in a high level of operational burden for the firm (Bode & Wagner, 2015; Borgatti & Li, 2009; Kim et al., 2011; Kim et al., 2015). Consequently, a firm's ability to mitigate or respond to disruptions decreases as the number of supply chain partners increases (Bode & Wagner, 2015).

Density is a network-level measure and captures the level of connectedness in the network (Kim et al., 2011). Conceptually, there has been support for both a positive and a negative link between network density and resilience (Choi & Krause, 2006; Kim et al., 2015). On the one hand, if there are redundancies in inter-

relationships among other members of the supply network, the network could be more resilient to the removal of one of these links (Janssen et al., 2006). However, dense networks can propagate the impact of a supply chain disruption across the supply network and increase the systematic risk in the network (Scheibe & Blackhurst, 2018). In addition, a high number of inter-relationships can increase the coordination costs of disruption recovery efforts (Craighead et al., 2007).

Past studies have explored how supply network complexity affects efforts to recover from supply chain disruptions. However, to our knowledge, there is no research to date that investigates how the complexity of firms' supply networks changes after experiencing such disruptions. Considering the evidence of the negative role of supply network complexity in preventing and recovering from supply chain disruptions, firms that have recently experienced such disruptions may choose to restructure their supply networks to reduce their complexity. We aim to contribute to these underexplored questions around the dynamic nature of supply networks, which we discuss in the next section.

2.2. Structural changes of supply networks

Most empirical research on supply networks has taken a static view, with a limited focus on the evolution of network structure (Park et al., 2018). Changes in networks form one of the least explored areas in network research (Gulati et al., 2000; Madhavan et al., 1998; Suiitor et al., 1997; Venkatraman & Lee, 2004). This is probably a consequence of early network research where it was assumed that a network structure is a "given" rather than deliberately created by its members (Nohria & Eccles, 1992) and that these structures persist over time (Burkhardt & Brass, 1990; Burt, 1988; Doreian, 1986). Indeed, some networks, such as an acquaintance network,

tend to be fairly stable (Madhavan et al., 1998). Inter-firm networks, including supply networks, on the other hand, are dynamic (Gulati et al., 2000; Park et al., 2018). This is because inter-firm networks are critical in providing firms with access to resources and knowledge they do not possess (Gulati et al., 2000) and those networks need to be restructured in line with the changing needs of firms.

There are two perspectives on what shapes network structures through time: The endogenous perspective focuses on the drivers from within the network that spur change, whereas the exogenous perspective considers the external forces that prompt network changes (Gulati et al., 2000; Walker et al., 1997; Zaheer & Soda, 2009).

The endogenous view of structural change considers the past network structure as a predictor of the future network structure (Rosenkopf & Padula, 2008; Park et al., 2018; Zaheer & Soda, 2009). Furthermore, internally-driven changes occur for two reasons: (1) cohesiveness and (2) prominence (Rosenkopf & Padula, 2008). Cohesiveness refers to the phenomenon of firms tending to choose a partner from among those with which they had direct or indirect links in the past (Rosenkopf & Padula, 2008). This is mainly due to the fact that prior interactions can provide information about the capability and trustworthiness of these partners, which are vital in mitigating exchange hazards (Artz & Brush, 2000; Lumineau & Henderson, 2012; Poppo et al., 2008). Prominence, on the other hand, builds on the observation that firms that exhibit high network centrality tend to have disproportionately more opportunities for forming new ties (Kim, 2015; Rosenkopf & Padula, 2008), since centrality signals its reputation or power.

Network changes can also have exogenous origins. Companies can be compelled or forced to modify the structure of their networks as a response to a major

external shock (Li et al., 2010; Madhavan et al., 2008) in order to gain or maintain access to knowledge and resources. For example, the advent of new technology often encourages or forces firms to venture out of their usual networks to create ties with new firms in order to access novel knowledge and innovation (Bellamy et al., 2014; Borgatti & Li, 2009; Li & Rowley, 2002). Other examples of external shocks that lead to changes in network structures are regulatory changes and the entry of a powerful competitor (Madhavan et al., 1998; Li et al., 2010). However, there has been a dearth of studies that consider catastrophic disasters as exogenous origins.

In this study, we take the exogenous perspective and consider catastrophic supply chain disruptions as external shocks that can bring changes to supply network structures. The majority of research on network changes, however, has focused on the endogenous factors and more studies are needed on the exogenous factors of network changes (Madhavan et al., 1998; Rosenkopf & Almeida, 2003; Park et al., 2018; Walker et al., 1997; Zaheer & Soda, 2009). Furthermore, as mentioned earlier, extant research on the external forces of network changes has not paid attention to catastrophic supply chain disruptions as the external shock, where, unlike technological innovations or regulatory changes, the onset is very sudden. In addition, although supply network complexity has been shown to negatively affect firms' risk mitigation and disruption recovery efforts, it remains unclear how the complexity of the supply network changes after major supply chain disruptions. This research seeks to fill these gaps in the literature.

3. HYPOTHESIS DEVELOPMENT

This paper investigates whether the catastrophic supply chain disruptions

caused by *the earthquake* led to structural changes in the affected firms' supply networks. In the following paragraphs, we hypothesize that the supply network complexity of affected companies will diminish after such catastrophic disruptions, both as a result of their actions and those of their partners, and the business environment. In line with past studies that adopt the NK model to conceptualize supply network complexity (Choi and Krause, 2006; Kim et al., 2015), we capture supply network complexity through the focal firm's centrality—both in-degree and out-degree centrality to capture the supplier and customer sides, respectively—and its ego network density.

In-degree centrality dictates the level of influence a firm has in its network and the quality and the quantity of resources it is able to access through its partners (Bellamy et al., 2014; Borgatti & Li, 2009; Provan et al., 2007). However, firms that have a high level of in-degree centrality on the supply side also tend to face significant coordination challenges (Kim et al., 2011). The high number of suppliers increases the frequency and complexity of transactions for the buying firm, creating various operational pressures (Bode & Wagner, 2015; Kim et al., 2011; Kim et al., 2015). This would suggest that high in-degree centrality could undermine a firm's efforts to respond to a supply chain disruption. If, as suggested by previous research, the complexity of its supplier network impeded a firm's efforts to respond to a recent catastrophic disruption effectively, the firm could attempt to reduce the number of suppliers and rationalize the size of its supply base after the disruption.

Furthermore, the firm's existing ties with other companies can become a gateway for the propagation of an upstream disruption (Bode & Wagner, 2015; Borgatti & Li, 2009; Kim et al., 2015). When considering the dimension of network

complexity that focuses on the number of the companies in a supply network (Bode & Wagner, 2015; Kim et al., 2015), in-degree centrality indicates the likelihood of the firm being impacted by the propagation of an upstream disruption. Therefore, a firm that has experienced this recently within its supply network is more likely to be driven to streamline its supply base.

Finally, firms are constantly on the lookout for new suppliers that can provide quality components and services as well as new knowledge and innovation (Wagner, 2012; Yan et al., forthcoming). This activity of adjusting the network needs to be supported by a munificent environment (Koka et al., 2006) as well as the firms' own resources. A major natural disaster reduces structural, infrastructural, and/or financial resources, thus in turn, reducing environmental munificence. Moreover, responding to catastrophic supply chain disruptions requires a company-wide resource mobilization, relegating other needs of the firm, including tie creation, to a secondary position. Thus, reduced environmental munificence as well as available resources within the firm will slow down a buying firm's tie creation activities with new suppliers. For these reasons, we hypothesize that:

Hypothesis 1: Firms that experience catastrophic supply chain disruptions will have fewer suppliers after the disruption, compared to the firms that do not experience the disruption.

Similar to the buying firms that would attempt to reduce their supply network complexity by reducing their number of suppliers after experiencing catastrophic disruptions, customers of affected firms will also aim to reduce complexity by streamlining their supply networks. This is partially due to the propagation effect discussed earlier. If a firm is affected by supply chain disruption, that disruption will

be propagated to some, if not all of its customers (Han and Shin, 2016). Therefore, the firms that are known to have been affected by a major disruption could face difficulties in keeping some existing customers and attracting new ones, at least temporarily.

Furthermore, even if customers prefer to continue their relationship with the focal firm, the impact of the disruption on the financial health of the customers may make it untenable. Disruptions tend to lead to a number of unplanned expenses and restrict access to financial resources, which can lower customers' liquidity and cash reserves. Simultaneously, customers can experience higher levels of demand uncertainty themselves. Catastrophic natural disasters are, therefore, often accompanied by a reduction in customer demand (Park et al., 2013).

In terms of attracting new customers, firms may face another challenge. Firms face significant pressures to grow by acquiring more customers. Such tie creation activity, however, requires significant resources. Furthermore, increases in the customer base tend to correspond to an increase in the resources needed to support these customers. In other words, growing the customer base and maintaining it requires a firm to have the resources, either within its own corporate boundaries or accessible through its business environment, to support its growth (Koka et al., 2006). As discussed earlier, a major natural disaster and the ensuing catastrophic supply chain disruption tends to deplete the internal and external resources necessary to support creating new links. Therefore, we hypothesize:

Hypothesis 2: Firms that experience catastrophic supply chain disruptions will have fewer customers after the disruption, compared to the firms that do not experience the disruption.

A dense ego supply network with many inter-relationships among the focal firm's supply chain partners can expose the focal firm to a high level of supply risk (Choi and Krause, 2006). If a supplier delivers products to other suppliers or customers of a focal firm, an event that disrupts the supply network is more likely to affect the focal firm's operations negatively. For example, when a system or industry level disruption (e.g., *the earthquake*) increases demand or supply volatility, multiple companies in the network simultaneously rush to secure alternative supply. In a dense network, this could lead to resource cannibalization, where a supplier's capacity that could have been allocated to the focal firm's demand is directed to other players in the focal firm's network (Lee et al., 1997). Similarly, in a tightly connected supply network, an accident at a supplier can disrupt a focal firm's operations both directly and indirectly through other buying firms who also supply to the focal firm (Scheibe & Blackhurst, 2018). This "supply chain disruption propagation" is more pronounced in supply networks where supply chain partners across multiple tiers of the supply chain are connected with each other (i.e., in supply networks with higher ego network density).

In addition, responding to a supply chain disruption requires extensive coordination between a buyer and its supplier for collective sense-making (Johnson et al., 2013; Krause et al., 2007) and resource mobilization (Ambulkar et al., 2015; Olcott & Oliver, 2014). Responding to catastrophic supply chain disruptions may sometimes require joint efforts at the network-level (Olcott & Oliver, 2014). When such network-level efforts are required, connections among the focal firm's supply chain partners can come at additional coordination costs for firms involved (Choi & Krause, 2006; Choi & Wu, 2009; Craighead et al., 2007). This would be especially

true for large companies with a high number of supply chain partners. The consequence of experiencing these coordination costs during the recovery period is likely to put a downward pressure on ego network density.

After experiencing a major supply chain disruption, firms would realize the dangers of supply chain disruption propagation and challenges of coordinating during recovery in densely connected supply networks. Therefore, firms with recent experience of a major supply chain disruption would be expected to simplify their networks. If several firms that are directly or indirectly connected to the focal firm decide to reduce their number of direct ties, the cumulative effect of these firm-level decisions should also lower the ego supply network density for the focal firm. Therefore, we hypothesize:

Hypothesis 3: Firms that experience catastrophic supply chain disruptions will have lower ego supply network density after the disruption, compared to the firms that do not experience the disruption.

4. METHODOLOGY

4.1. Empirical setting and data

In this paper, we seek to explore how firms' supply networks change following catastrophic supply chain disruptions. For this, we selected *the earthquake* as an exogenous force that drives structural changes in supply networks. One useful approach to understanding exogenous factors' impact on structural changes of a network is to consider "occasions for structuring" (Barley, 1986). This approach assumes that exogenous factors can be captured through a specific event that affects network structures. This event needs to be a major shock that disturbs the competitive

landscape on a large scale with lasting impact (Barley, 1986; Madhavan et al., 1998).

This paper investigates the 2011 Tōhoku earthquake and tsunami in Japan as a major disaster that serves as an occasion for restructuring the supply networks of affected firms. The reason for selecting *the earthquake* is that it is considered the “single largest and broadest natural disaster in recent times” causing significant, catastrophic supply chain disruptions and consequently, operational and financial damage to multiple firms operating in Japan (Sheffi, 2015: p. ix), and, therefore, is more likely than smaller-scale events to impact supply network structures.

To build our sample, we used as our starting point the 2011 Forbes Global 2,000 list, which captures the world’s largest public companies. Next, using the Global Industry Classification Standard (GICS), we excluded firms from service sectors such as finance, banking, and insurance, leaving 934 firms in our initial sample from nine sectors as described by the Forbes Global industry list. These sectors include consumer discretionary, consumer staples, energy, healthcare, industrials, information technology, materials, telecommunications, and utilities. The financial data of the 934 initial sample firms were collected from the Orbis database.

Furthermore, we used the FactSet supply chain relationship database to identify these firms’ supply network structures. This database comprises records of contractual buyer-supplier relationships of more than 20,000 companies compiled from their financial regulatory filings (e.g., 10-K reports), company websites, and press releases. Using this database, we constructed a network for each firm that consists of their customers and suppliers, the customers’ customers and suppliers, and the suppliers’ customers and suppliers.

4.2. Measures

Based on the networks, we calculated the in-degree centrality, out-degree centrality, and ego network density for each firm. We measured each of these variables as follows: In-degree centrality was captured by a count of the first-tier suppliers, whereas out-degree centrality was measured as the total number of direct customers (Kim et al, 2011). Ego network density was calculated as the ratio of the sum of the number of existing relationships between the focal firm and its supply chain partners as well as those between the partners to the total number of *all possible* relationships between these supply chain network members (Kim et al., 2011). We calculated these variables using UCINET 6.3. One point to note for ego network density is that UCINET calculates network density by using the ratio explained above and multiplying this number by 100. These three network measures were subsequently used to calculate the dependent variables of our study, which are explained in the following section.

We used industry sector dummy variables and pre-earthquake (2010) financial variables (log of total assets, log of the number of employees, log of inventory, return-on-assets, cost-of-goods-sold-to-sales, cash-to-sales, and debt-to-equity) to control for industry and firm-specific factors. The variables were also used during the process of propensity score matching, which is explained in more detail in Section 4.3.

4.3. The difference-in-differences approach

To capture the changes in supply network structures after *the earthquake*, we computed the differences between pre- and post-earthquake supply network variables (Δ *In-degree centrality*, Δ *Out-degree centrality*, and Δ *Ego network density*). The differences were computed by subtracting the values of supply network variables measured one year prior to *the earthquake* (2010) from the values of the same

variables measured one year after *the earthquake* (2012). These differenced measures were used as the dependent variables.

Afterwards, we compared these dependent variables of the firms in the treatment group (the Japanese firms affected by *the earthquake*) with those of the firms in the control group (the firms not affected by *the earthquake* but with characteristics similar to the treatment group). We explain our process in the next sections.

4.3.1. Treatment group

From the initial sample of 934 Forbes Global 2000 firms, we selected those in the treatment group based on two criteria. First, they have headquarters in Japan. Second, these firms experienced *the earthquake* in 2011 and reported consequential operational damages in their annual reports at the end of the same fiscal year. We downloaded the 2011-2012 annual reports from Thomson Reuters ONESOURCE. We identified 76 Japanese firms that experienced operational damages from *the earthquake* and assigned all these 76 firms to the treatment group. As a visual example of the impact of *the earthquake*, Figure 1 shows the ego supply network diagrams of two companies in the treatment group before (2010) and after (2012) *the earthquake*.

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4.3.2. Establishing the control group using propensity score matching

We employed propensity score matching to construct a sample of control group firms that did not report operational damages caused by *the earthquake* and have industry- and firm-level characteristics similar to the treated firms. These control group firms were selected from the 934 initial sample firms. The propensity score

matching procedure calculates the conditional probability of assignment to the treatment group using the probit estimation with observed covariates (Rosenbaum & Rubin, 1983). The calculated probabilities from the probit estimation, the propensity scores in this context, are then used to determine the similarities between the characteristics of the treated and untreated observations. Typically, an untreated observation that has the nearest propensity score to a treated observation is assigned to the control group.

As discussed earlier, structural changes of a supply network can be induced by exogenous forces as well as endogenous forces and past network characteristics, (Gulati et al., 2000; Walker et al., 2000; Zaheer & Soda, 2009). This means that it is necessary that the firms in the treatment and control groups have similar ego supply network structures before *the earthquake*. We used the number of suppliers, number of customers, and ego network density measured in 2010 for selecting control firms that share similar network characteristics with treated firms.

In addition, we used industry sector dummy variables and pre-earthquake (2010) financial variables (log of total assets, log of the number of employees, log of inventory, return-on-assets, cost-of-goods-sold-to-sales, cash-to-sales, and debt-to-equity) as additional matching criteria. The economics and finance literature commonly uses these financial variables as matching criteria (e.g., Almeida et al., 2012). Each firm in the treatment group is matched with one control firm that has the nearest propensity score to the treated firm, yielding the final sample of 152 firms. Table 1 shows that there are no significant mean differences between the treatment and control groups in terms of matching characteristics.

-- INSERT TABLE 1 ABOUT HERE --

4.3.3. Statistical model

We indicate differences between pre- and post-earthquake supply network variables (Δ In-degree centrality, Δ Out-degree centrality, and Δ Ego network density) as Δ Network_{*i*} and set up the following regression equation to estimate the impact of *the earthquake* on the supply network structure:

$$\Delta \text{ Network}_i = \beta \times \text{Earthquake}_i + \gamma' X_i + \varepsilon_i,$$

where *i* indicates the firm and Earthquake is a binary variable that equals one for the treatment group and zero for the control group. *X* is the vector of control variables explained in Section 4.3.2 and ε is the error term. Since Δ Network_{*i*} denotes the change in the supply network structure after *the earthquake*, the sign of the regression coefficient β effectively indicates whether the change for the treatment group is positive or negative compared to that for the control group.

5. RESULTS

5.1. Main results

Table 2 shows the impact of *the earthquake* on the three dependent variables: Δ In-degree centrality, Δ Out-degree centrality, and Δ Ego network density. Models 1, 3, and 5 are base models with control variables only, while Models 2, 4, and 6 include the treatment variable, Earthquake. The significant negative coefficients for Earthquake in Model 2 ($\beta = -9.63$, $p < 0.001$), Model 4 ($\beta = -3.49$, $p = 0.003$), and Model 6 ($\beta = -0.91$, $p = 0.034$) provide support for H1, H2, and H3, respectively. These results suggest that, compared to the firms in the control group, the firms which were affected by *the earthquake* had reduced levels of in-degree, out-degree, and ego network centralities.

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5.2. Robustness checks

To check whether our findings are robust to using different time lags in calculating the dependent variables, we computed alternative measures of the dependent variables by subtracting the values of the network structure variables measured in 2010 from those measured in 2011 and 2013. The results from Models 7 through 11 in Table 3 are consistent with the main results that support H1 and H2. However, the non-significant coefficient for Earthquake in Model 12 ($\beta = -0.16$, $p = 0.691$) suggests that two years after *the earthquake*, the firms that were affected by it did not have reduced levels of ego network centrality compared to the firms in the control group. Therefore, we conclude that H3 is only partially supported.

-- INSERT TABLES 3 AND 4 ABOUT HERE --

In addition, to examine whether the differences in the dependent variables between treatment and control groups are driven by *the earthquake* or any pre-existing trend before *the earthquake* in 2011, we tested whether the two groups had parallel trends in 2009 and 2010. For this pre-earthquake parallel trend analysis, we computed the differences in the three dependent variables (Δ *In-degree centrality*, Δ *Out-degree centrality*, and Δ *Ego network density*) by subtracting 2009 values from 2010 values. Table 4 shows that there are no statistically significant differences between the treatment and control groups (i.e., non-significant coefficient for Treatment) in the three dependent variables measured before *the earthquake*. This result indicates that the two groups had similar trends in in-degree centrality, out-degree centrality, and ego network density prior to *the earthquake* and strengthens the evidence that the differences between treatment and control groups after *the*

earthquake are caused by *the earthquake*.

6. DISCUSSION

6.1. Theoretical contributions

Our paper contributes to the supply network literature by investigating whether catastrophic supply chain disruptions caused by exogenous events, such as the 2011 Tōhoku earthquake and tsunami, lead to significant structural changes in the supply networks of the affected companies. Extant empirical studies on supply networks have mostly focused on whether and how the network structure impacts operations and business performance (e.g., Bellamy et al., 2014; Bode & Wagner, 2015; Lu & Shang, 2017) with limited attention given to drivers of changes in supply network structures. In the context of supply chain resilience, the complexity perspective has been applied to understand the impact of supply network structure on vulnerability to disruptions and recovery from them. It has been suggested that the complex network structures make the supply chain more vulnerable, and therefore, complexity has generally been considered a barrier to responding to disruptions effectively (e.g., Bode & Wagner, 2015; Choi & Krause, 2006; Scheibe & Blackhurst, 2018). Yet the question of how supply network structures change after major supply chain disruptions has remained unanswered.

Our analysis shows that the firms that were disrupted by *the earthquake* have seen a reduction in the number of their suppliers compared to the firms that were not. This finding contributes to the literature on the relationship between supply network complexity and supply chain resilience. Previous research on supply network complexity and supply chain risk or resilience has established that a relatively simpler

supply network structure would (1) have a lower likelihood of upstream disruptions being propagated to the buying firm (Bode and Wagner, 2015; Perrow, 1984) and (2) enhance the buying firm's recovery efforts through less coordination burden with its suppliers (Bode and Wagner, 2015; Borgatti and Li, 2009; Kim et al., 2011; Kim et al., 2015).

Our results show that, in addition to the above, after firms experience catastrophic supply chain disruptions, they also witness changes in their supply network structures tending toward lower complexity. We reviewed multiple possible reasons for this, some were initiated by the company and others driven by their supply chain partners or the new reality of the business environment. Although we cannot distinguish the exact drivers, what is clear is that, in our sample, there is a shift toward less complex supply chain structures.

Our results resonate with the complexity perspective, which also brings into question an alternative perspective on how the supply chain structure relates to supply chain resilience. The redundancy view postulates that having a larger number of redundant suppliers can be beneficial for the buying firm's performance in responding to disruption, since the larger the supplier base, the higher the likelihood of finding available capacity and capability among its suppliers (Lomi & Pattison, 2006; Sheffi & Rice, 2005). If that is the case, we would expect an increase in the number of suppliers. We did not find support for this argument. Still, we need to be cautious with this assessment; the disruption may also trigger supply network changes where less proactive and less efficient suppliers are replaced with more proactive and efficient suppliers. The net effect could still be lower numbers of suppliers. Alternatively, the decrease in firm resources and environmental munificence due to

the disruptions may make it difficult for affected firms to manage multiple redundant suppliers. Then, even if the firm's preference would be to increase the number of redundant suppliers after the disruption, they may not be able to do so. Identifying precise reasons for these changes would be an interesting avenue for future study.

Our findings also suggest that the firms affected by *the earthquake* have reduced numbers of customers compared to the firms that did not report disruptions caused by *the earthquake*. Unlike the changes observed in the number of suppliers, the reduction in the number of customers, that is the out-degree centrality, after *the earthquake* is not likely to be the focal firm's deliberate response to the disruption. Extant literature in supply chain management has investigated the impact of upstream network complexity on disruption mitigation and recovery (e.g., Bode & Wagner, 2015; Kim et al., 2015). Other than the fact that there has been a missed research opportunity on the downstream side of the supply chains, we would also argue that this question deserves attention as the driving force of the post-disruption changes in the supplier and customer sides are likely to be fundamentally different and may require different responses from the focal firm. The firms that experienced catastrophic supply chain disruptions do not have an incentive to deliberately decrease the number of customers and risk losing additional sales opportunities. Rather, the reduction in the post-disruption number of customers is likely to be driven largely by the existing and potential customers' efforts to reduce complexity in their upstream supply networks. As a part of their own supply chain risk management strategies, for example, customers of the firms that experienced severe supply chain disruptions may not retain those firms as suppliers (Polyviou et al., 2018). Similarly, potential customers may also be reluctant to establish new buyer-supplier relationships with the

firms that experienced severe supply chain disruptions. Moreover, the company-wide recovery efforts by the focal firm impacted by a severe supply chain disruption often require significant resource reprioritization (Ambulkar et al., 2015; Bode et al., 2011). This could result in a reduction in the amount of resources available for attracting new customers.

In addition, our analysis provides empirical evidence that firms that are impacted by major supply chain disruptions tend to have reduced levels of ego network density compared with those unaffected by the disruptions. Past literature has considered the performance implications of high ego network density for focal firms. For instance, buying firms can obtain operational benefits through the suppliers that are connected to each other, in the form of access to additional resources or information pooling and sharing (Choi & Wu, 2009; Wu & Choi, 2005). Some buying firms are known for actively encouraging connections between their suppliers (Dubois & Fredriksson, 2008; Wu & Choi, 2005) or creating ties with lower-tier suppliers (Chae et al., 2019; Choi & Linton, 2011) increasing the ego network density in their supply networks. However, it has also been suggested that an increase in the ego network density may have detrimental results; interconnections among customers may negatively influence suppliers' profitability (Kim, 2017). In the context of supply chain disruptions and recovery, interconnections among between the supply chain partners could increase the likelihood of a disruption being propagated to the buying firm and bring additional coordination challenges in the recovery efforts (Choi & Krause, 2006; Han & Shin, 2016; Scheibe & Blackhurst, 2018).

Our findings imply that buying firms and their customers may prefer maintaining lower levels of ego network density in their supply networks after

realizing through major supply chain disruptions the challenges associated with the high level of inter-dependencies (i.e., higher ego network density) in managing supply chain risks. On the other hand, a different body of the supply chain risk and resilience literature suggests that close relationships among partners would be useful in responding to catastrophic supply chain disruptions since they generate social capital for network-level sense-making and resource mobilization (Olcott & Oliver, 2014; Ambulkar et al., 2015). Similar to the results for the centrality measures, our findings provide empirical support that, after a catastrophic disruption, firms face lower supply network complexity in the form of a decreased level of ego network density compared to unaffected firms.

Finally, previous studies have provided empirical evidence that supply chain disruptions can inflict short-term financial loss to buying firms (Hendricks & Singhal, 2003, 2005a, 2005b), yet their longer-term non-financial consequences have not been explored. Our study provides a starting point in understanding whether catastrophic supply chain disruptions could inflict long-term strategic damage to affected firms by limiting (1) the growth in the number of customers and, hence, the potential for additional future revenue generation and (2) the discovery of new suppliers for improving its competitiveness such as innovation creation.

6.2. Managerial implications

There has been a significant amount of research that helps managers better understand what capabilities they should invest in to build resilience. We draw the managers' attention back to the vulnerability side of supply chain resilience for two reasons. First, supply network complexity, which has some advantages during business as usual, may become an impediment during times of crisis. Given that

crises, particularly catastrophic events such as natural disasters, are increasing at an alarming rate (Sodhi, 2016), striking a balance between these two states will become an ever-present challenge. Second, our results show that companies are finding themselves facing a new reality in their supply networks after catastrophic disruptions. Accepting this as well as disentangling the internal and external drivers of this change can help managers anticipate and respond more effectively after the disruption. Given the devastating effects of such disruptions, it is easy to understand why our focus until now has been more on the antecedents of these disruptions. We now invite managers to start reflecting on the structural changes in supply networks after disruptions.

Companies that choose to maintain a large number of supply chain partners do so because the scale determines (1) the quality and the quantity of resources and knowledge available to them (Bellamy et al., 2014; Borgatti & Li, 2009; Kim et al. 2011; Provan et al., 2007) and (2) the level of redundancy required to secure resources (Lomi & Pattison, 2006; Sheffi & Rice, 2005; Uzzi, 1996). Similarly, some buying firms have been encouraging their supply chain partners to connect to each other (Dubois & Fredriksson, 2008; Wu & Choi, 2005) since such inter-connectedness could potentially support the development of trust, reciprocity and shared identities across the network (Granovetter, 1992; Gulati et al., 2000; Lazarrini et al., 2001). Such ties and buffers can be valuable when there are fewer and less severe disruptions. However, the subsequent complexity can significantly slow down firms' effective response to major disruptions. If this is the case, managers will reassess their position after such disruptions and simplify their supply network, which is in line with what we see in our results.

However, there is also the question of whether some of these changes are imposed by the firm's partners and the external business environment. Depending on the impact of these external drivers, managers should at least be aware of the changes that will be imposed on their supply networks and ideally have drawn up contingency plans for these new challenges, as shown by our results.

In summary, managers face the difficult question of how to balance supply network needs during normal business cycles with those experienced during disruptions. While striking an optimal balance is going to be difficult, given the very dynamic nature of the context, awareness of the different realities is the first step in preparing for and managing the impact of supply chain disruptions.

6.3. Limitations and future research

This study is based on the supply chain disruptions caused by one major natural disaster, the 2011 Tōhoku earthquake and tsunami. As one of the first empirical attempts to examine the impact of catastrophic supply chain disruptions on supply network structures, we chose the “single largest and broadest natural disaster in recent times” (Sheffi, 2015: p. ix) as our empirical setting. Nevertheless, the impact of this event was largely limited to Japanese firms. Although Japanese firms provide a unique, ideal context characterized by interdependent ties and dense networks (Lazzarini et al., 2001; Ouchi, 1980), the patterns of network changes after supply chain disruptions could be different in other national contexts.

Moreover, natural disasters are one of many causes of supply chain disruptions. Therefore, we call for more future studies that investigate the impact of supply chain disruptions on supply network structural changes under broader conditions including diverse national contexts and different sources of supply chain

disruption, such as trade conflicts and epidemics.

We also note that, although we provide evidence on how supply network structures change after major supply chain disruptions, the performance implications of those changes remain ambiguous. Future research could study how the supply network structural changes made after supply chain disruptions relate to the post-disruption resilience of those supply networks.

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Table 1. Comparison of matching characteristics between treatment and control groups

Matching characteristics	Group	Observations	Mean	p-value (t-test)
In-degree centrality	Treatment	76	11.66	0.97
	Control	76	12.01	
Out-degree centrality	Treatment	76	6.36	0.39
	Control	76	7.84	
Ego network density	Treatment	76	0.97	0.25
	Control	76	1.40	
Log Assets	Treatment	76	16.82	0.66
	Control	76	16.89	
Log employees	Treatment	76	10.55	0.74
	Control	76	10.61	
Log inventory	Treatment	76	14.43	0.68
	Control	76	14.51	
ROA (%)	Treatment	76	2.97	0.75
	Control	76	2.73	
COGS-to-sales	Treatment	76	0.65	0.97
	Control	76	0.65	
Cash-to-assets	Treatment	76	0.15	0.61
	Control	76	0.16	
Leverage	Treatment	76	1.90	0.52
	Control	76	2.05	

Table 2. The impact of the earthquake on supply network structures

	DV: Δ In-degree centrality		Δ Out-degree centrality		Δ Ego network density	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Earthquake		-9.631*** (2.015)		-3.490** (1.170)		-0.907* (0.422)
In-degree centrality	0.481** (0.154)	0.540** (0.157)	0.109† (0.064)	0.131* (0.062)	-0.024 (0.017)	-0.018 (0.016)
Out-degree centrality	-0.627** (0.237)	-0.708** (0.210)	-0.128 (0.105)	-0.157 (0.105)	0.024 (0.027)	0.016 (0.027)
Ego network density	0.326 (0.290)	0.150 (0.319)	0.510 (0.353)	0.446 (0.300)	-0.607* (0.306)	-0.624* (0.291)
Log assets	3.172 (2.280)	2.288 (2.127)	1.408 (1.571)	1.088 (1.527)	-0.302 (0.418)	-0.385 (0.410)
Log employees	2.028 (1.386)	1.895 (1.374)	0.366 (0.891)	0.318 (0.917)	0.666* (0.291)	0.654* (0.280)
Log inventory	-0.125 (1.456)	-0.088 (1.271)	-0.611 (1.261)	-0.598 (1.225)	-0.092 (0.286)	-0.089 (0.267)
ROA	0.234 (0.252)	0.336 (0.269)	-0.552** (0.187)	-0.516** (0.187)	-0.080 (0.052)	-0.071 (0.051)
COGS-to-sales	5.727 (5.843)	5.419 (5.683)	-21.369*** (4.588)	-21.480*** (4.416)	2.385† (1.417)	2.356 (1.344)
Cash-to-assets	1.187 (8.187)	-4.576 (8.947)	5.217 (6.974)	3.128 (6.873)	-0.071 (1.696)	-0.614 (1.717)
Leverage	1.916 (1.335)	1.504 (1.269)	2.767* (1.364)	2.618† (1.331)	-0.119 (0.129)	-0.158 (0.131)
Sector dummy	Included	Included	Included	Included	Included	Included
Constant	-97.437** (34.238)	-64.926† (34.531)	-33.612 (20.524)	-21.831 (19.796)	-1.665 (5.947)	1.396 (5.802)
R-squared	0.493	0.572	0.363	0.392	0.295	0.320
Observations	152	152	152	152	152	152

Robust standard errors in parenthesis. † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3. Robustness checks

	DV:	Δ In-degree centrality		Δ Out-degree centrality		Δ Ego network density	
	Year:	2011	2013	2011	2013	2011	2013
		Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Earthquake		-3.303** (1.256)	-8.734*** (2.203)	-2.719** (0.904)	-4.182** (1.436)	-0.983* (0.400)	-0.155 (0.389)
In-degree centrality		1.105*** (0.096)	0.586** (0.188)	0.156* (0.073)	0.042 (0.104)	-0.022 (0.016)	-0.013 (0.015)
Out-degree centrality		-0.050 (0.099)	-0.583* (0.234)	-0.274** (0.089)	-0.209 (0.145)	0.046 (0.028)	0.006 (0.023)
Ego network density		0.071 (0.197)	0.126 (0.347)	0.201 (0.158)	0.262 (0.291)	-0.682** (0.213)	-0.428* (0.193)
Log assets		4.389* (1.793)	2.474 (2.370)	-0.336 (0.969)	3.671* (1.753)	0.601 (0.643)	-0.087 (0.424)
Log employees		-0.350 (0.905)	2.154 (1.459)	0.383 (0.629)	-0.078 (0.964)	0.791* (0.312)	0.491 (0.298)
Log inventory		-0.373 (1.138)	1.047 (1.505)	0.308 (0.789)	1.059 (1.526)	-1.510 (0.725)	-0.497 (0.261)
Return-on-assets		0.091 (0.130)	0.268 (0.275)	-0.299* (0.122)	-0.529 (0.227)	-0.004 (0.051)	-0.019 (0.047)
COGS-to-sales		-3.071 (3.510)	6.673 (6.159)	-16.431*** (3.080)	-15.637** (4.526)	3.766* (1.831)	3.298* (1.297)
Cash-to-assets		5.322 (7.048)	-1.220 (10.208)	2.491 (5.081)	0.083 (0.718)	-2.119 (1.543)	0.970 (02.187)
Leverage		1.822 (1.400)	1.664 (1.516)	2.077* (1.029)	-0.349 (0.240)	-0.133 (0.136)	-0.322* (0.131)
Sector dummy		Included	Included	Included	Included	Included	Included
Constant		-80.790** (25.629)	-88.106* (39.513)	-7.049 (17.353)	-50.924† (29.400)	1.319 (6.049)	6.780 (6.322)
R-squared		0.920	0.610	0.444	0.211	0.459	0.255
Observations		152	152	152	152	152	152

Robust standard errors in parenthesis. † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

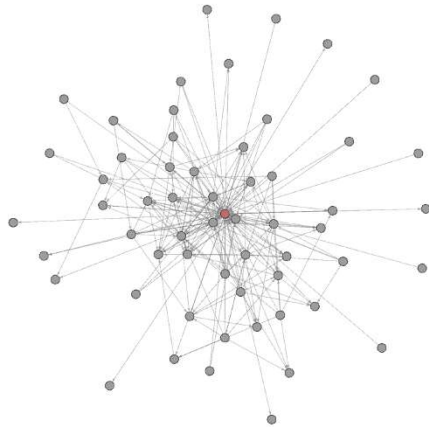
Table 4. Parallel trend in the pre-disruption phase

	DV:	Δ In-degree centrality	Δ Out-degree centrality	Δ Ego network density
	Year:	2010	2010	2010
Treatment		-1.145 (0.772)	-0.474 (0.466)	-0.216 (0.320)
Constant		0.026 (0.460)	1.553*** (0.375)	-0.200 (0.131)
R-squared		0.014	0.007	0.003
Observations		152	152	152

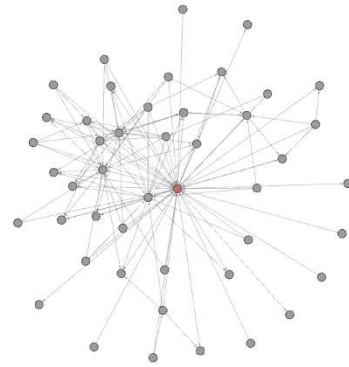
Robust standard errors in parenthesis.

† $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

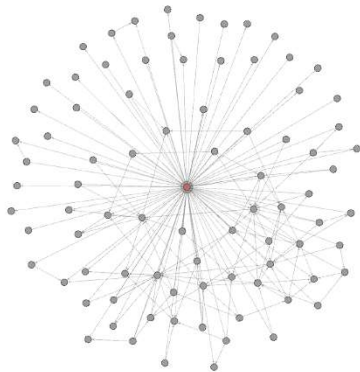
Figure 1. Ego supply networks before and after *the earthquake*



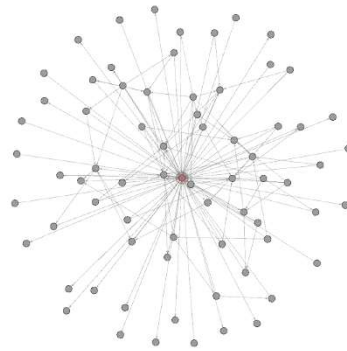
Canon ego supply network in 2010



Canon ego supply network in 2012



NEC ego supply network in 2010



NEC ego supply network in 2012