Journal of Economic Geography **20** (2020) pp. 809–856 doi:10.1093/jeg/lbz020
Advance Access Published on 2 August 2019

Natural disasters and trade: the mitigating impact of port substitution

Masashige Hamano[*] *and Wessel N. Vermeulen*[**,†]

[*]Faculty of Political Science and Economics, Waseda University, 1-104 Totsuka, Shinjuku-ku, Tokyo 169-8050, Japan
[**]Business School, Newcastle University London, 102 Middlesex street, London E1 7EZ, UK
[†]Correspondence to: *email* <wessel.vermeulen@newcastle.ac.uk>

Abstract

We study the effect of natural disasters on port-level exports. We model the interaction between firms and ports to study how strongly exports from one port are affected by changes in the cost of exporting at neighboring ports. We extend the standard trade model with heterogeneous firms to a multiple port structure where exporting is subject to port specific local transportation costs, port specific fixed export costs and international bilateral trade costs. We show that gravity distortion due to firm heterogeneity is conditional on the comparative advantage at the port level and resulting substitution of exports across ports. We present evidence of the substitution effect using the 2011 Great East Japan Earthquake, indicating that at least 40% of exports was substituted to other ports following the disaster. The substitution effect is the strongest in technology intensive product categories, which suggests an interaction between supply chains and domestic trade costs.

Keywords: Firm heterogeneity, extensive margins, transportation costs, fixed costs, natural disasters
JEL classifications: F14, O18, R1
Date submitted: 23 January 2019 **Editorial decision:** 20 June 2019 **Date accepted:** 10 July 2019

1. Introduction

Natural disasters, such as hurricanes, typhoons and earthquakes shock the world frequently and have large economic impacts on national and regional economies. High population density, economic growth and climate change are all contributing factors to the increasing economic toll of natural disasters. To make societies more resilient to future shocks it is important to understand how people, businesses and governments deal with this growing threat.[1] One area of research is to understand disaster risk

---

[1] See, for instance, for developing economies Gignoux and Menéndez (2016) studying long-run welfare effects of earthquakes in Indonesia and Kirchberger (2017) studying related labor markets of one specific earthquake in 2006; De Mel et al. (2011) on the recovery of business activity in Sri Lanka following the Tsunami of 2004 in South-East Asia; Islam and Nguyen (2018) provide evidence of household resource sharing within their informal networks following cyclone Aila in Bangladesh. For developed economies: labor market outcomes are studied by Belasen and Polachek (2008) in counties in Florida, USA, affected directly or indirectly by hurricanes and by McIntosh (2008) in Louisiana, USA, following hurricane Katrina in 2005 with a spillover of immigrant workers to Texas. Also following hurricane Katrina, Deryugina (2017) and Deryugina et al. (2017) study individual outcomes using fiscal data; Hallstrom and

assessment and individual perceptions of risk (Aerts et al., 2018). Another area, to which we contribute, addresses the resilience of an economy to withstand and adapt to major (natural) disasters (Kahn, 2005).

In the aftermath of a disaster, during the process of recovery, firms, business and people try to restore and rebuild their livelihoods. This includes the ability of firms to bring their goods to export markets, thereby ensuring their continued operations. In turn, this will mitigate the total economic damage and likely support and accelerate economic recovery. Disasters in coastal areas and port cities in particular will not only affect the businesses in the affected city, but also those in the wider region that use the port facilities of that city. The potential of firms to substitute between ports after disasters has been considered in civil engineering literature (Trepte and Rice, 2014; Akakura and Ono, 2017). To the best of our knowledge we are the first to model this mechanism using micro-foundations and estimate the substitution effect using detailed port-level export data.

In most developed economies, firms have a number of ports to choose from to export their products. Therefore, we first develop a model in which firms select ports to export, and derive the condition under which multiple ports are in use simultaneously by different firms. Second, we investigate when and which firms switch between ports if the costs of using one port change relative to another and derive the implications for port-level exports. Third, we estimate using port-level data from Japan the extent of the substitution effect.

Building on a Melitz-Chaney framework (Melitz, 2003; Chaney, 2008), we develop a model where firms in an economy are served by multiple ports. Each port is associated with specific fixed and variable costs, which can vary by sector.[2] The level of firm productivity interacts with the ports' specific variable and fixed costs analogously to the familiar framework of firm selection into trade. We derive the conditions that regulate how firms choose different ports, such that in equilibrium an economy exports from multiple ports simultaneously. As port specific costs of trade change in one port relative to another it becomes optimal for some firms to switch between ports. This will lead to a decrease in total exports from the port that saw its costs increase and an increase in exports from its closest substitute, with other ports unaffected.

We test this prediction using data at the level of month-port-product-destination from Japan around the period of the March 2011 Great East Japan Earthquake which caused a tsunami. This disaster damaged a number of ports on the northeastern

---

Smith (2005) study house prices following hurricane Andrew in 1992. The effect of firms is studied by Cole et al. (2019), Hosono et al. (2016) and Tanaka (2015) following the Great Hanshin-Awaji (Kobe) earthquake of 1995; by Volpe Martinicus and Blyde (2013) following infrastructure destruction from an earthquake in Chile in 2010; and by Barrot and Sauvagnat (2016) and subsequently by Hsu et al. (2018) for natural disasters in the USA over 30 years. Cross-country perspectives are given by Fomby et al. (2013) who study dynamic growth effects, and Gassebner et al. (2010) who study the effect of natural disasters on aggregate international trade using a panel dataset with yearly data. This overview is far from exhaustive, and many more studies are cited in the before mentioned articles. For a further literature review on the economics of natural disasters see also Cavallo and Noy (2011).

[2] Variable costs approximate the costs associated with bringing goods from plants to the port, which could be affected by distance and domestic transport facilities, as well as port specific facilities such as the costs paid for each shipment. Port specific fixed costs relate to further costs of using port facilities that are independent of the shipment size, such as the efficiency of administrative facilities the capacity of warehousing and the natural and physical conditions of port that affect the entry and exit of ships. That port facilities and their costs are crucial determinants in international trade has been recognized (Clark et al., 2004; Feenstra and Ma, 2014).

Honshu coast in the Tohoku region. Their facilities were damaged and the rubble floating in the sea limited ships entry to and exit from ports.[3] Other ports, further away, especially in Keihin area (the three prefectures around Tokyo bay, Chiba, Tokyo and Kanagawa) and on the side of the Sea of Japan in Hokuriku region, were not directly affected by the natural disaster and played the role of substitution ports for producers in the affected area. As the port counterfactual we use all other ports in Japan, who were far away from the disaster region.

Our estimations indicate that for some months, an average substitution port gained up to 30% additional trade in terms of value. Overall, during the first 12 months after the earthquake, our estimates suggest that around 40% of the exports was substituted to other ports, however, once we control for lost industrial output this number increases to 89%. We find that most of this substitution effect is due to the adjustment in the set of product varieties (i.e. the *extensive margins* (*EMs*) *of trade*). These product varieties, however, are small in size and provide only a limited impact in terms of scale of export (i.e. the intensive margins (IMs) of trade) and hence the total value, in line with our theoretical predictions. Additionally, we find large differences between sectors and across destination regions. This heterogeneity suggests that goods that are subject to pressures from supply chains or perishability are most likely to be substituted.

The 2011 Great East Japan Earthquake has been analyzed using firm-level data. Todo et al. (2015) explore the role of local supply chain networks on firms recovery time using survey data. Cole et al. (2017) investigate the role of pre-disaster planning on post-disaster firm-level performance. Zhu et al. (2016) study the decision of off-shoring of Japanese firms in the aftermath of the disaster. The use of annual firm-level data implies some limitations for the analysis and the identification of mechanisms. Carvalho et al. (2016) study the propagation of the shocks across Japan using input–output linkages from detailed firm-level data for 3 years. In contrast to these studies, we can better control for pre-tsunami circumstances and closely follow the dynamics of the recovery and substitution.

Boehm et al. (2019) study the effect the disaster had on US manufacturing, in particular when differentiating between Japanese affiliates and others. Japanese affiliates source a larger fraction of their intermediates from Japan and were therefore affected relatively more. Due to the specificity of Japanese differentiated goods and ‘just-in-time’ supply chains the international spill-over is amplified. Hsu et al. (2018) suggest that there are firms characteristics that make them more adaptable to the consequences of natural disasters. What we indicate is that there are also factors outside the firm that can decrease the potential of supply chain disruptions, notably the use of alternative ports. This mechanism offers a path toward government policy to increase economic resilience and decrease international supply chain disruptions in the face of natural disasters. Our limitation is that we must focus on Japanese ports rather than firms and, therefore, we complement these firm-level studies.

Finally, Volpe Martinicus and Blyde (2013) test the effect of firm-level shipments following the 2009 earthquake in Chile that destroyed a large portion of the transport

---

[3] Among the main nine ports in Tohoku region, it took more than 250 days on average to recover 80% of berths (Ono et al., 2016). In contrast, inland roads recovered quickly (the main roads on the side of the Pacific Ocean from the affected area to Kanto area including highways were reopened the day after the earthquake), and most firms in the disaster area were operational within 1–2 weeks (Todo et al., 2015; Cole et al., 2017).

network. However, they find no port substitution effect in exports. Sytsma (2017) studies port exports in the USA following hurricanes in the period of 2003–2015, instead of using a single event as we do in this article, but does not look explicitly at the potential of port substitution.

2. The model

We start with the description of the theoretical model and thereafter explain the specific empirically motivated three-ports case, namely tsunami-hit ports and substitute ports relative to an unaffected counterfactual. Our model builds on the heterogeneous firms framework of Melitz (2003) following Chaney (2008). There are N number of countries in the world. In a country n, there are multiple ports, k, whose total number is exogenously given by K_n. The country's total population, which equals the labor supply, is also exogenously given by L_n. In each country, sector 0 provides homogeneous goods, which serve as a *numéraire* and are traded worldwide without any transportation cost while other sectors, h, whose total number is H, produce differentiated goods. Each firm is heterogeneous in terms of their productivity level and produces one product variety in monopolistically competitive markets. We do not model multiple-products/plants aspect of firms explicitly. However, the setup of the model can be interpreted as a single large firm that has heterogeneous multiple product lines.[4] In our model, firms choose a specific port for exporting.[5]

2.1. Households

Households of a typical country gain utility from the consumption of a set of differentiated product varieties in each sector, Ω_h, as well as homogeneous goods (omitting country-specific subscripts for readability):

$$C = c_0^{a_0} \prod_{h=1}^{H} \left(\int_{\Omega_h} \Big(q(\omega) c(\omega) \Big)^{1-\frac{1}{\sigma_h}} d\omega \right)^{\frac{a_h}{1-\frac{1}{\sigma_h}}},$$

where c_0 is the consumption of homogeneous goods whose price serves as *numéraire*. The consumption of a particular product variety, $c(\omega)$, is either produced locally or imported. The 'quality' of that good, $q(\omega)$, can be interpreted as an exogenous demand shifter, which is origin-destination(-sector) specific. The elasticity of substitution of product varieties in each sector is given by σ_h (>1). The expenditure weight on homogenous goods is given by a_0 and that on goods in sector h is given by a_h.

2.2. Ports and firms

Firms in country i are assumed to be heterogeneous in terms of their specific labor productivity level, φ, and are facing the following choice: export or not export, and if

---

[4] For instance, for the model with multiple-product firms (Bernard et al., 2010). Also for simplicity, we exclude the possibility of foreign direct investment (FDI) as in Helpman et al. (2004).

[5] The essential feature of our model is the ability of heterogeneous firms to choose between ports, and that this choice is affected by a fixed and a variable cost. This is the reason why we take Melitz-Chaney paradigm rather than Bernard et al. (2003), which does not embed fixed cost for exporting. For the importance of fixed costs in international trade, see for instance Eaton et al. (2004).

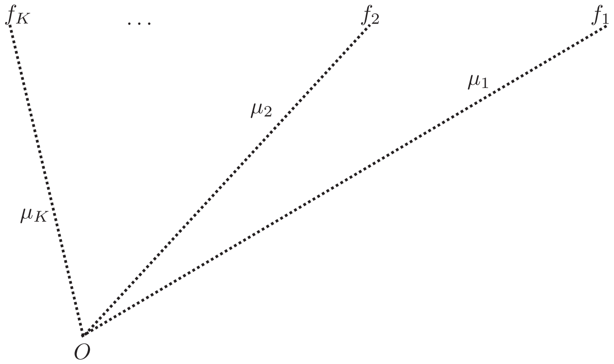

Figure 1. Multiple ports within country.
Notes: Ports, counted $k = 1,\ 2, \ldots, K$. The fixed costs of ports, $k = 1, \ldots, k$ are represented by f_k. The effective costs of distance from firms located in O to port k, μ_k, vary.

export, a choice in ports. Production involves only labor as input. Exporting from an origin country i to a destination country j requires port specific fixed costs, f_{ijk}, and port k specific iceberg type local (within country) transportation costs, μ_k (> 1), as well as an iceberg type of bilateral trade costs, $\tau_{ij}(>1)$.[6]

For a firm with a specific productivity, φ, total costs in producing y units of a good and exporting these goods of country i of port k to country j is thus given by

$$TC_{ijk}(\varphi) = \frac{w_i \mu_k \tau_{ij}}{Z_i \varphi} y + f_{ijk},$$

where w_i denotes real wages in country i and the level of labor productivity, Z_i, is common for all firms in country i. We have dropped sector index h in the above expression for the simplicity of notation and focus on firms in a specific sector.[7] Figure 1 summarizes the setting of our model.

2.3. Demand for differentiated goods

Due to monopolistic competition, production scale is determined by demand. The demand addressed to the firm that has a productivity level φ from a destination country j is given by

$$c_{ijk}(\varphi) = q_{ij}^{\sigma-1} \left(\frac{p_{ijk}(\varphi)}{P_j} \right)^{-\sigma} \alpha C_j, \tag{2.3.1}$$

where P_j is the ideal price index for a particular sector in country j and

$$p_{ijk}(\varphi) = \frac{\sigma}{\sigma - 1} \frac{w_i \mu_k \tau_{ij}}{Z_i \varphi}. \tag{2.3.2}$$

---

[6] Note that $\tau_{ij} > 1$ for $i \neq j$ and $\tau_{ii} = 1$.

[7] In particular, we can consider μ_k and f_{ijk} to be sector specific.

If the firm exports from port k, dividends are given by $d_{ijk}(\varphi) = p_{ijk}(\varphi)c_{ijk}(\varphi) - TC_{ijk}(\varphi)$. Plugging the demand (Equation (2.3.1)) and optimal price (Equation (2.3.2)) into the dividends equation, we get

$$d_{ijk}(\varphi) = \frac{1}{\sigma}\left(\frac{p_{ijk}(\varphi)/q_{ij}}{P_j}\right)^{1-\sigma}\alpha Y_j - f_{ijk}, \tag{2.3.3}$$

where Y_j is total income or total expenditure of country j, namely, $Y_j = P_j C_j = w_j L_j(1+d)$ with d as the dividends from a global mutual fund that collects and distributes dividends from all over the world. Following Chaney (2008), we assume that the share of dividends is proportional to the total labor income of each country and that the potential number of entrants in exporting market is proportional to the total labor income in the country, $w_j L_j$. Specifically, the latter assumption simplifies the analysis by abstracting from free entry of firms.

2.4. Decision to export and port choice

A cutoff productivity level $\overline{\varphi}_{ijk}$ above which firms export is determined by $d_{ijk}(\overline{\varphi}_{ijk}) = 0$ for each port. By solving the above zero-profit-cutoff (ZPC) condition, we have:

$$\overline{\varphi}_{ijk} = \lambda_1\left(\frac{w_i\mu_k\tau_{ij}}{Z_i q_{ij} P_j}\right)\left(\frac{f_{ijk}}{Y_j}\right)^{\frac{1}{\sigma-1}}, \tag{2.4.1}$$

where $\lambda_1 = (\sigma/\alpha)^{\frac{1}{\sigma-1}}[\sigma/(\sigma-1)]$. Note that the cutoff level is port specific due to port specific local transportation costs μ_k and port specific fixed export costs f_{ijk}.

Having computed the cutoff productivity level for each port, we rank them as[8]

$$\overline{\varphi}_{ijK_n} < \overline{\varphi}_{ijK_n-1} < \ldots < \overline{\varphi}_{ij2} < \overline{\varphi}_{ij1}. \tag{2.4.2}$$

For any pair of cutoff productivity level $\{\overline{\varphi}_{ijk}, \overline{\varphi}_{ijl}\}$, with $k = 2, \ldots, K_n$ and $k > l$, we can further define another cutoff productivity level for which firms are indifferent in exporting from either port. This cutoff level between ports, $\overline{\varphi}_{ijkl}$, is defined by the even-profit-cutoff (EPC) condition, $d_{ijk}(\overline{\varphi}_{ijkl}) = d_{ijs}(\overline{\varphi}_{ijkl})$. Solving this condition we have

$$\overline{\varphi}_{ijkl} = \lambda_1\left(\frac{w_i\tau_{ij}}{Z_i q_{ij} P_j}\right)\left[\frac{f_{ijl} - f_{ijk}}{Y_j\left(\mu_l^{-(\sigma-1)} - \mu_k^{-(\sigma-1)}\right)}\right]^{\frac{1}{\sigma-1}}. \tag{2.4.3}$$

Two competing ports k and l have different port specific features with respect to local transportation costs and fixed export costs. This cutoff is meaningful in the following sense. Firms with productivity level $\overline{\varphi}_{ijkl}$ will be indifferent between exporting through port k and l. For these firms, the relative variable costs and relative fixed costs exactly yield the same profit. To make this more concrete, we can say that one port, say l, is more efficient in terms of local transportation costs, but less efficient in terms of its fixed export costs than port k. Therefore, firms choose either ports k or l, depending on their level of labor productivity φ, and therefore both ports will export some goods.

---

[8] Note that the above ranking is just a conceptual device which eases the reasoning that follows. Thus this is not an assumption on the model, but for convenience of representation and without loss of generality.

Formally, we can establish a *port comparative advantage* in the following proposition.

Proposition 1: Under $f_{ijl}/f_{ijk} > (\mu_l/\mu_k)^{1-\sigma} > 1$ for $k = 2\ldots K_n$ with $k>$1, we have $\overline{\varphi}_{ijk} < \overline{\varphi}_{ijl} < \overline{\varphi}_{ijkl}$. In this case, firms with $\overline{\varphi}_{ijkl} < \varphi$ prefer to export from port s while firms with $\overline{\varphi}_{ijk} < \varphi < \overline{\varphi}_{ijkl}$ prefer to export from port k and multiple ports are in action. Port k is said to have a comparative advantage in fixed export costs, while port l has a comparative advantage in variable costs.

Proof. See Appendix A.1. When $(\mu_l/\mu_k)^{1-\sigma} > 1$, a marginal increase in profits of exporting from port *l* is higher than that from port *k* for firms with $\overline{\varphi}_{ijkl} < \varphi$. Therefore, exporters spread into either port with which they earn higher exporting profits. Having established EPC productivity levels for any pairs of port provided by the ranking of zero profit cutoff productivity levels for each port as in Equation (2.4.2), the firm with φ eventually chooses to export from one specific port k^* that maximizes its exporting profits $d_{ijk^*}(\varphi)$. See also Figure 2 where we provide a specific case with $K_n = 3$. Finally, note that Proposition 1 holds for each sector.

When $(\mu_l/\mu_k)^{1-\sigma} < 1$, however, firms absolutely prefer to export from port *k* independent of their productivity level and we have the following corollary.

Corollary 1: *When* $\mu_1 > \mu_2 > \ldots > \mu_{K_n-1} > \mu_{K_n}$, *all exporters export from port* K_n.

By removing the port comparative advantage, the port K_n has now absolute advantage in both fixed export costs and local transportation costs, which results in attracting all local exporters.

Having established the above export decision and port decision, we can compute the ideal price index in country *j* as

$$\left(\frac{\sigma-1}{\sigma}P_j\right)^{1-\sigma} = \sum_{n=1}^{N} w_n L_n \left[\int_{\overline{\varphi}_{njK_n}}^{\overline{\varphi}_{njK_nK_n-1}} \left(\frac{w_n \mu_{K_n} \tau_{nj}}{Z_n q_{nj}}\right)^{1-\sigma} dG(\varphi) + \ldots \right. \\ \left. + \int_{\overline{\varphi}_{nj21}}^{\infty} \left(\frac{w_n \mu_1 \tau_{nj}}{Z_n q_{nj}}\right)^{1-\sigma} dG(\varphi)\right]. \tag{2.4.4}$$

2.5. Tsunami hit and substitute port

We can now think of a structure of the model that fits our empirical strategy and data. Therefore, we look at the comparative statics at the port–sector level. First, we regroup ports into three categories and let each be represented by their mean of the ports in each category, with abuse of notations, namely group of ports *H*, ports *S* and ports *C*. Ports in group *H* are those hit by tsunami at the Great East Japan Earthquake. The ‘tsunami hit’ ports are mainly in Tohoku region.[9] Ports in group *S* are exposed to potential substitution of exporting from port *H*. The ‘substitute’ ports are hence in areas neighboring Tohoku. Ports in group C are neither tsunami hit nor substitutes. These ‘counterfactual’ ports are geographically far from Tohoku and neighboring areas.

For the simplicity of the presentation, we also assume a three port-group-structure in the rest of the world. To solve the model we assume the Pareto distribution for firm

---

[9] See the map of Figure 3 on page 14.

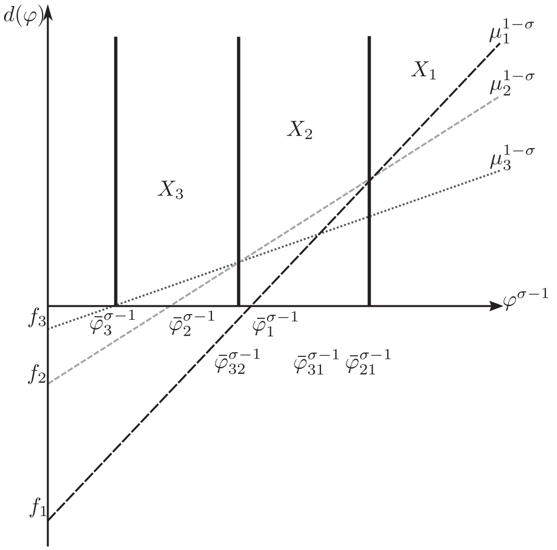

Figure 2. Multiple port in action ($K_n = 3$).

Notes: A representation of export allocations for a specific sector over three ports that have different levels of fixed and effective variable costs. Firms will choose the port that offers the highest profits given their level of productivity, ϕ. Each port offers a minimum level of productivity with which exports become profitable, $\overline{\phi}_k^{\sigma-1}$. For each combination of two ports, there exists a level of productivity with which a firm would be indifferent between either port, $\overline{\phi}_{kl}^{\sigma-1}$.

specific productivity level as $G(\varphi) = 1 - \varphi^{-\kappa}$ where κ ($>\sigma - 1$) is the shape parameter of the distribution. When κ increases, firms are more concentrated at its minimum level of productivity, which we set as unity. Using the Pareto distribution and plugging the cutoff levels (2.4.1) and (2.4.3) in the ideal price index (2.4.4) together with the definitions of the substitute and hit ports, we have

$$P_j = \lambda_2 Y_j^{\frac{1}{\kappa}-\frac{1}{\sigma-1}} \vartheta_j,$$

where $\lambda_2 = [(1+d)/Y][\kappa - (\sigma-1)/\kappa][\sigma/(\sigma-1)]^{\kappa}(\sigma/\alpha)^{\frac{\kappa}{\sigma-1}-1}$, Y denotes world GDP and

$$\vartheta_j^{-k} = \sum_{n=1}^{N} \frac{Y_n}{Y}\left(\frac{w_n \tau_{nj}}{Z_n q_{nj}}\right)^{-\kappa}\left[f_{njS}^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\mu_S^{-\kappa} + (f_{njH} - f_{njS})^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\left(\mu_H^{-(\sigma-1)} - \mu_S^{-(\sigma-1)}\right)^{\frac{\kappa}{\sigma-1}}\right]. \tag{2.5.1}$$

Thus ϑ_j is the weighted average of origin and destination specific characteristics capturing the 'remoteness' of country j from the rest of the world. Different from the expression in Chaney (2008), however, the term includes the efficiency of ports in each county in the square bracket. Conventionally, the impact stemming from changes in bilateral trade cost of country n is considered to be negligible in ϑ_j.[10]

---

[10] Similarly, we assume that any changes in port-specific costs are negligible as $\partial\vartheta_j/\partial f_{njH} = \partial\vartheta_j/\partial f_{njS} = \partial\vartheta_j/\partial\mu_H = \partial\vartheta_j/\partial\mu_S = 0$.

With the above closed-form solution, exporting sales of firm φ that exports from Japan (country i) to country j, $x_{ijk}(\varphi) = p_{ijk}(\varphi)y_{ijk}(\varphi)$ with $k = H$ or S, can be expressed as

$$\begin{aligned} x_{ijH}(\varphi) &= \lambda_3\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i\mu_H\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)^{1-\sigma}\varphi^{\sigma-1}, \text{ if } \overline{\varphi}_{ijSH} < \varphi, \\ x_{ijS}(\varphi) &= \lambda_3\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i\mu_S\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)^{1-\sigma}\varphi^{\sigma-1}, \text{ if } \overline{\varphi}_{ijS} < \varphi < \overline{\varphi}_{ijSH}, \\ &\quad 0 \text{ otherwise,} \end{aligned} \tag{2.5.2}$$

where $\lambda_3 = \sigma\lambda_4^{1-\sigma}$ and $\lambda_4^{\kappa} = [1/(1+d)][\kappa/\kappa-(\sigma-1)](\sigma/\alpha)$. Cutoff productivity levels are also rewritten as

$$\overline{\varphi}_{ijS} = \lambda_4\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i\mu_S\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)f_{ijS}^{\frac{1}{\sigma-1}},$$

$$\overline{\varphi}_{ijSH} = \lambda_4\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)\left(\frac{f_{ijH}-f_{ijS}}{\mu_{ijH}^{-(\sigma-1)}-\mu_{ijS}^{-(\sigma-1)}}\right)^{\frac{1}{\sigma-1}}.$$

2.6 Gravity

Exports from tsunami-hit port H are given by $X_{ijH} = w_iL_i\int_{\overline{\varphi}_{ijSH}}^{\infty} x_{ijH}(\varphi)dG(\varphi)$ while those from substitute port S are given by $X_{ijS} = w_iL_i\int_{\overline{\varphi}_{ijS}}^{\overline{\varphi}_{ijSH}} x_{ijS}(\varphi)dG(\varphi)$. Thanks to the closed-form expression, we can derive a gravity equation for each port. The level of exports from port H is given by

$$X_{ijH} = \alpha\frac{Y_iY_j}{Y}\left(\frac{w_i\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)^{-\kappa}\mu_H^{-(\sigma-1)}\left(\mu_H^{-(\sigma-1)}-\mu_S^{-(\sigma-1)}\right)^{\frac{\kappa}{\sigma-1}-1}(f_{ijH}-f_{ijS})^{-\left(\frac{\kappa}{\sigma-1}-1\right)}. \tag{2.6.1}$$

The level of exports from port S is given by

$$\begin{aligned} X_{ijS} &= \alpha\frac{Y_iY_j}{Y}\left(\frac{w_i\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)^{-\kappa} \\ &\left[\mu_S^{-\kappa}f_{ijS}^{-\left(\frac{\kappa}{\sigma-1}-1\right)}-\mu_S^{-(\sigma-1)}\left(\mu_H^{-(\sigma-1)}-\mu_S^{-(\sigma-1)}\right)^{\frac{\kappa}{\sigma-1}-1}(f_{ijH}-f_{ijS})^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\right]. \end{aligned} \tag{2.6.2}$$

Total exports from country i to j is thus given by

$$\begin{aligned} X_{ij} &= X_{ijS}+X_{ijH} \\ &= \alpha\frac{Y_iY_j}{Y}\left(\frac{w_i\tau_{ij}}{Z_iq_{ij}\vartheta_j}\right)^{-\kappa}\left[\mu_S^{-\kappa}f_{ijS}^{-\left(\frac{\kappa}{\sigma-1}-1\right)}-\left(\mu_H^{-(\sigma-1)}-\mu_S^{-(\sigma-1)}\right)^{\frac{\kappa}{\sigma-1}}(f_{ijH}-f_{ijS})^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\right]. \end{aligned}$$

Note that by abandoning the assumption of $\mu_S > \mu_H$, all firms export from substitute port S and the expression collapses to a similar one as in Chaney (2008).

2.7. Margin decomposition

In this subsection, we discuss the decomposition of trade flow as in the literature (Chaney, 2008; Head and Mayer, 2014). For the sake of notational simplicity we drop origin and destination index, i and j, when there is no room for confusion. Export flow from each port can be decomposed as $X_H = N_{XH}\tilde{x}_H$ and $X_S = N_{XS}\tilde{x}_S$, where $N_{XH} = wL\Big(1 - G(\overline{\varphi}_{SH})\Big)$ and $N_{XS} = wL\Big(G(\overline{\varphi}_{SH}) - G(\overline{\varphi}_S)\Big)$ represent the number exporters and

$$\tilde{x}_H = \left[\int_{\overline{\varphi}_{SH}}^{\infty} x_H(\varphi)dG(\varphi)/\Big(1 - G(\overline{\varphi}_{SH})\Big)\right]$$

and

$$\tilde{x}_S = \left[\int_{\overline{\varphi}_S}^{\overline{\varphi}_{SH}} x_S(\varphi)dG(\varphi)/\Big(G(\overline{\varphi}_{SH}) - G(\overline{\varphi}_S)\Big)\right]$$

capture the average export flow among these exporters from tsunami-hit port H and substitute port S, respectively. The number of exporters is called 'extensive margins'. The average export flow is further decomposed into 'intensive margins', i.e. the changes in average export scale given a cutoff productivity level, and 'composition margins' (CMs), i.e. the remaining impact on average export flow induced by changes in the cutoff productivity level. We provide the result of comparative statics analysis of each component in total export flow induced by exogenous variables. Namely, we compute

$$\frac{d\ln X_k}{d\ln v} = \frac{d\ln N_{Xk}}{d\ln v} + \frac{d\ln \tilde{x}_k}{d\ln v},$$

where $k = H$ or S, v is τ, Z, q, f_H and μ_H, and $d\ln \tilde{x}_k/d\ln v$ includes both IMs and CMs. Appendix A.2 presents all results on the comparative statics of changes in the trade margins.

To demonstrate the effect of changes of fixed and variable cost on the trade margins in the case of Japanese ports we present a numerical simulation. The parameter value of the elasticity of substitution and the extent of product heterogeneity are set as $\sigma = 6$ and $\kappa = 10$, respectively. These values are in line with the literature that considers disaggregated trade data (Romalis, 2007; Head and Mayer, 2014). The steady state level of port specific fixed cost and internal transportation cost of each tsunami-hit H and substitute S port are found based on the mean values of tsunami-hit ports and substitute ports prior to the Great East Japan Earthquake.[11]

---

[11] Namely, we find the steady state value of f_H, μ_H and μ_S that minimize the distance between empirical moments and implied theoretical moments using the Matlab optimization solver with constraints, fmincon. The empirical moments that we target are the relative pre-mean share, EMs and IMs of tsunami-hit port and substitute ports, which are summarized in Table 2. These moments are $X_H/X_S = 0.40/2.27$, $EM_H/EM_S = 8.63/23.47$ and $IM_H/IM_S = 3.81/4.64$. The above procedure gives $\bar{f}_H = 39.94$, $\overline{\mu}_H = 0.76$, $\overline{\mu}_S = 1.14$, while we set $\bar{f}_S = 1$ without loss of generality at the initial steady state.

Table 1. Simulation of an effect of port costs on trade, decomposed by trade margin

Elasticities	EM	IM	CM	Total
$d\ln X_H/d\ln f_H$	−2.05	0.00	1.03	−1.03
$d\ln X_S/d\ln f_H$	0.06	0.00	0.15	0.21
$d\ln X_H/d\ln \mu_H$	−11.53	−5.00	5.76	−10.76
$d\ln X_S/d\ln \mu_H$	0.34	0.00	0.83	1.17

Notes: Simulation results for both ports of a shock to a tsunami-hit (H) port represented by its fixed f_H and variable μ_H cost. The effects are measured in percentage points deviations from steady state following a 1% shock. Steady state margins are based on empirical margins of Japanese ports. See main text for further underlying assumptions.

Having in mind a port and road destruction in Tohoku region, in Table 1 we only report the results following a port specific fixed export cost shock and internal transportation cost shock in tsunami-hit port, namely, a one percentage point increase in f_H and μ_H, respectively.[12] First, following a one percentage point increase in f_H, due to a larger steady state size of S (substitute) ports compared to H (hit) ports in terms of export share ($X_H/X_S = 0.18$), EMs ($EM_H/EM_S = 0.37$) and IMs ($IM_H/IM_S = 0.82$), there is a *smaller* adjustment for substitute S port in all types of margins. For instance, EMs decrease by −2.05 percentage points for tsunami-hit H port while those for substitute S port increases by 0.06 percentage points. Second, following the shocks, for hit ports, the adjustment takes place at the lower end of distribution. Hence, exit of such low productivity firms has only a minor impact on the total value of exports combined with an increase in CM. On the other hand, for substitute ports, the same shocks induce the entry of exporters at the higher end of distribution providing a substantial positive impact on the total value of exports. The above-mentioned patterns are similar for internal transportation costs shock, μ_H, but with a larger magnitude in our simulation.

3. Empirics

3.1. Empirical setup

The theoretical model, Equations (2.6.1) and (2.6.2), suggests the following linearized equation of exports,

$$\ln X_{kht} = \text{constant} + a\ln\mu_{kht} + b\ln\mu_{lht} + c\ln f_{kht} + d\ln f_{lht},$$

with subscripts as in the theoretical model, k and l for port, h for sector and t for time. The constant captures a port's export pattern, such as world demand, pre-determined industrial structure and output around the port, which are arguably uncorrelated with the Tsunami event. From this equation, port destruction will affect ports differently depending on whether the shock is on the own port k, or to another port l. The only variables in the theoretical model that vary over k or l are the internal trade costs toward the ports and the fixed cost associated with each port μ_k, μ_l, f_k and f_l (omitting

---

[12] The numerical results for other types of shocks are available upon on request.

subscripts *i* and *j*). There is *a priori* no clear way to disentangle the variable from the fixed costs in our setup. Therefore, we assume that the outcome that we measure on trade is the sum of the effect that the tsunami had on the variable and the fixed costs, i.e. $a + c$ for the ports hit by the tsunami, and $b + d$ for the substitutes.

The regression model we estimate is

$$y_{gkt} = \sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{hit},v} \cdot \text{I}(v) \cdot \text{I}(\text{hit}_k) + \sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{sub},v} \cdot \text{I}(v) \cdot \text{I}(\text{sub}_k) + \beta_z z_{gkt} + \theta_{gk} + \alpha_{gt} + \epsilon_{gkt}, \tag{3.1.1}$$

$$g = \text{sectors } (h)/\text{destinations } (j);\ \ \text{k} = 1, \ldots, 119;\ \ t = \text{Jan 2009}, \ldots, \text{Dec 2012},$$

where, in line with the notation of the theoretical model, *g* indicates groups, such as sectors *h* or destinations *j*, *k* indicates ports and *t* indicates monthly time periods. Our main analysis will be done at the sector–port (*hk*) level, rather than destination-port (*jk*), so in the following we will refer to *g* as sectors for exposition. The left-hand-side variable y_{gkt} will be one of four trade variables of interest, log of export value (*lValue*), *EM*, *IM* and trade share (*TS*). The indicator functions $I(\text{hit}_k)$ and $I(\text{sub}_k)$ designate those sector–port combinations that are treated by the tsunami or as substitute, which we discuss in the next subsection. The indicator for port category is interacted with time indicators for the months from January 2011 to December 2012, $I(v)$.

We can add control variables to the regression, represented by z_{gkt} with corresponding coefficient β_z, to control for potential effects on local firms, further discussed in Section 3.4. The benchmark results will contain no control variables. Fixed effects are summarized by θ_{gk} for sector-by-port, and α_{gt} for sector-by-time. The first will capture ports' specializations into certain sectors, the second will capture nationwide sector development. For instance, the second would capture a nationwide energy supply shock on (energy intensive) sectors following the earthquake. If certain sectors would be concentrated in the tsunami-hit area, then this set of fixed effects would absorb some of the impact from the earthquake.

The parameters of interest are collected in the $\beta_{\text{hit},v}$'s and $\beta_{\text{sub},v}$'s, where v provides a separate label for each month. In combination with the indicator functions I(v), the coefficients for hit ports, $\beta_{\text{hit},v}$, and substitute ports, $\beta_{\text{sub},v}$, measure the combined effect of a shock on the fixed, f_H, and variable, μ_H on tsunami-hit ports for each period separately.

The estimated coefficients indicate the evolution of the outcome variables over the 24 months for the ports that are hit by the tsunami and those that we designated as potentially exposed to substitution. Through this setup, the effect of interest is estimated as the performance of a port relative to all other ports that were neither hit by the tsunami nor close enough to the hit port to be potentially treated as substitute ports, i.e. the counterfactuals, or in short 'others'. What we obtain through this setup is an average group effect for the two groups of ports relative to the rest. We cluster standard errors (s.e.) at the port level and present variation on the level of clustering below.

For the empirical identification we rely on the unexpected nature of the tsunami, which struck all ports on the same day. Although Japan is well adapted to the risk of earthquakes and the potential threat from tsunamis, the precise location, moment and magnitude of such events are random. This implies that ports were randomly assigned this ‘treatment’, while the force of the tsunami on 11 March 2011 was unprecedented in modern times. The tsunami was a devastating disaster for the coastal areas of the Tohoku and Kanto regions and around 16,000 people lost their lives. The earthquake had a magnitude of nine on the Richter scale, the strongest recorded for Japan ever, with the epicenter located 70 km off the coast at a depth of 30 km. The earthquake was followed by dozens of smaller quakes some with a magnitude of six or higher. Multiple waves hit the shore of north eastern Honshu (Tohoku) with heights up to 10 m from sea level (Ministry of Land, Infrastructure and Transport, 2011). The force of the wave made the water surge inland as much as 40 m above sea level, and in some areas a few kilometers from the coast, albeit these were local extremes.

Figure 3 presents a map of northern Japan giving an overview of the ports that were hit by the tsunami (squares) and all other ports (triangles and circles). From the Japanese Ministry of Land, Infrastructure and Transport (2011), we have the recorded tsunami-wave heights for each port. The ports closest to the earthquake epicenter were hit by the highest waves.

Apart from tsunami-hit ports we are principally interested in the response from ports that were *not* hit by the tsunami but regionally ‘close enough’ to be able to absorb additional exports from the firms in the Tohoku and Kanto region. We define these ports as substitutes, indicated with triangles in Figure 3. As further substitutes we allow ports in the Hokuriku and Tokai region to be impacted. The minimum, median and maximum distance between a hit and substitute port is 90, 736 and 1764 km, respectively. Robustness analysis on this selection of substitutes is discussed below. We assume that the ports further south-east in Japan, starting from the region of Kinki were too far away to be noticeably impacted. These ports are designated as the counterfactuals (circles). Since we found no effect of either hit ports or from substitutes in Hokkaido these ports are designated as counterfactual as well, but we change this designation in the robustness analysis.

3.2. Data and descriptive statistics

We obtained monthly export statistics from January 2009 to December 2012, for each customs office of Japan sea ports, with details on destination, value, quantity, at the nine-digit (six-digit HS codes with three-digit Japanese specific addition) product level from the Japanese Ministry of Finance website, which is freely available. We calculate export value (by time, sector/destination grouping and port) and the EMs and IMs of trade following Hummels and Klenow (2005). The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan.[13] A detailed description of data sources and the construction of the dataset is provided in Appendix B.1. Our main analysis will be with a single destination (the world) over a set of 19 sectors, which are defined in Appendix B.5.

Table 2 presents descriptive statistics for the four exports indicators over the three groups of ports averaged over the sectors. The full period includes the entire sample period from January 2009 to December 2012. The pre- and post-periods present the

---

[13] Our intensive margin should be seen as the sum of the intensive and compositional margin from the theory.

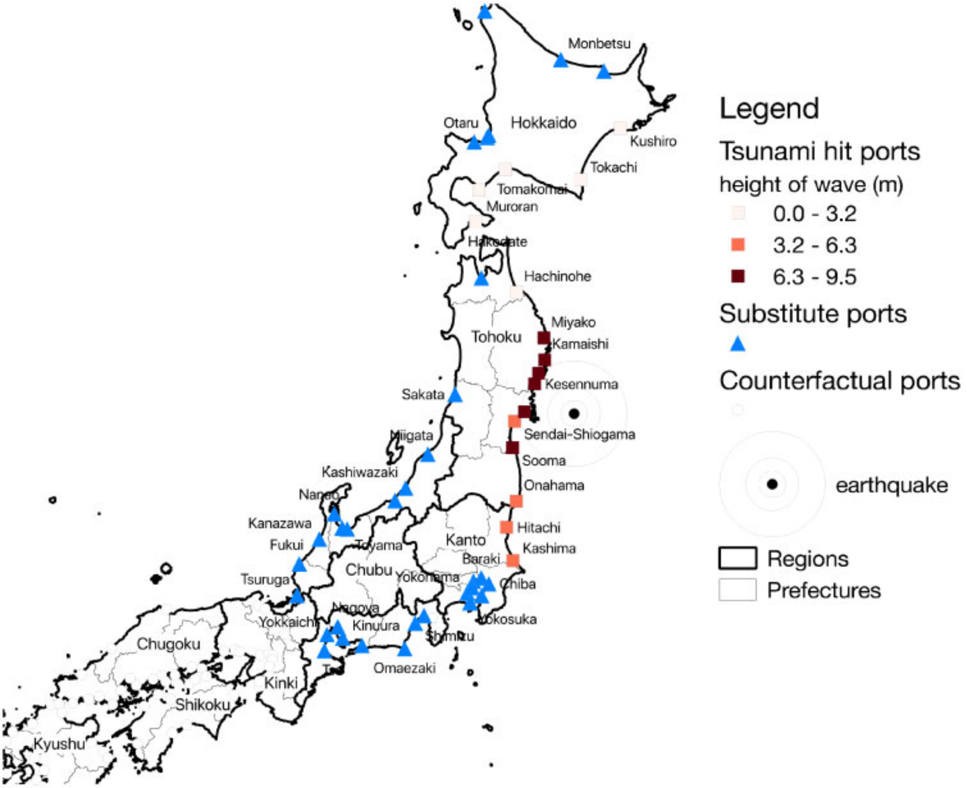

Figure 3. Tsunami hit, substitute and counterfactual ports.

Notes: Data on the height of the wave come from the Japanese Ministry of Land, Infrastructure and Transport (2011). The location of the earthquake comes from the US Geological Survey (2011) (http://earthquake.usgs.gov/earthquakes/browse/significant.php), but this information is not further used in our analysis. In the benchmark regression analysis, Hokkaido ports are not designated as treated. For reference, Tokyo is located just south of the tsunami-hit ports where a cluster of triangles denotes the various ports in the Tokyo area and the Fukushima Daiichi Nuclear power plant, which failed when it was flooded by the tsunami, is located at the coast of the most southern prefecture of the Tohoku region.

data for November 2010 to February 2011, and March 2011 to June 2011, respectively, with the last column presenting a simple t-test on the difference in means. As is evident from the EM, TS and number of varieties, the tsunami-hit ports are considerably smaller than the national average, while the substitutes, given that these include the ports around Tokyo, are considerably larger than the average. Density and distribution plots for the ports are presented in Appendix B.1. The t-test indicates a statistically significant drop in the EM, TS and IValue of tsunami-hit ports, but not in the IM. However, the test does not show a statistically significant effect for the substitute ports.

Figure 4 presents plots of the trade measures demeaned over the port group and sector for each month. These plots indicate how the mean of each of the three port-categories has evolved over time. The smooth-line represents a polynomial fit (with a 95% confidence band) based on all (demeaned) observations for a port-category, separately estimated for the pre- and post-tsunami periods. The sharp growth in the log

Table 2. Descriptive statistics

Measure	Group	Ports	Full mean	Full sd	Mean pre	sd pre	Mean post	sd post	Test
EM	Other	91	10.95	20.45	11.07	20.81	11.29	20.84	0.62
	Tsunami hit	15	7.16	12.71	8.63	14.45	5.19	10.38	0.00
	Substitute	27	24.65	29.40	24.59	29.66	25.04	29.53	0.68
	All	116	13.70	23.02	13.93	23.37	13.78	23.24	0.71
IM	Other	91	3.55	9.31	3.43	9.06	3.66	9.46	0.24
	Tsunami hit	15	3.82	11.28	3.81	10.54	2.95	10.16	0.11
	Substitute	27	5.14	9.54	5.14	9.74	4.91	9.28	0.52
	All	116	3.95	9.64	3.87	9.43	3.87	9.52	0.99
lValue	Other	91	10.99	2.95	11.03	2.96	11.07	2.97	0.57
	Tsunami hit	15	10.92	2.67	11.27	2.61	10.59	2.66	0.00
	Substitute	27	12.08	3.04	12.09	3.09	12.15	3.04	0.63
	All	116	11.31	2.99	11.37	3.00	11.35	3.01	0.80
TS	Other	91	0.78	2.99	0.77	2.91	0.82	3.08	0.42
	Tsunami hit	15	0.37	1.37	0.40	1.13	0.22	0.80	0.00
	Substitute	27	2.25	5.01	2.27	5.11	2.21	4.95	0.76
	All	116	1.07	3.51	1.07	3.49	1.07	3.52	1.00

Notes: Statistics, averaged over sectors and by period. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. The column 'ports' indicates the number of ports. Since the designation of substitution port is at the sector level, a port can be substitute for one sector, but counterfactual for another. Therefore, the combined value of substitute, hit and other is higher than the total number of ports. The columns 'full mean' and 'full sd' give the mean and standard deviation of the respective statistic over the entire sample period (2009–2012). The columns for 'pre' and 'post' indicate the same statistics based on a 4-Month pre-tsunami and post-tsunami period. The final column presents the p-value of a simple t-test on the differences between the two periods for each statistic.

of exports and the EM for all ports-groups in the pre-tsunami period is consistent with the recovery of the global trade collapse following the great financial crisis (See, for instance, Baldwin (2009), Ando and Kimura (2012) and Alessandria et al. (2013)).

The difference between the plots in panels (a) and (b) is the way the margins are demeaned. Plot (b) estimates the mean based on pre-tsunami months only, while in plot (a) the mean is estimated using the entire sample, which is equivalent to a standard fixed effect within-transformation. We note that the demeaned series in panel (a) suggest that before March 2011 the tsunami-hit ports were outperforming, while the substitution ports were underperforming the counterfactual ports. This apparent effect is not visible in panel (b). This difference can be explained with a large and long-term effect of the disaster on the treated ports, which is partially absorbed in the mean when estimated over the full time period. This suggests that a fixed effects estimation following model (Equation 3.1.1) will give a conservative estimate of the substitution effect. The lines of the three port categories in panel (b) are closely overlapping, suggesting that there are no differential trends between port-groups before the earthquake. The plots for the EM and log export value also suggest that some of our counterfactual experienced some positive effect in first few months immediately after the earthquake. We chose not to correct for this through a search for the ports that might be driving this result, but it will imply that our substitution effect might be conservatively estimated.

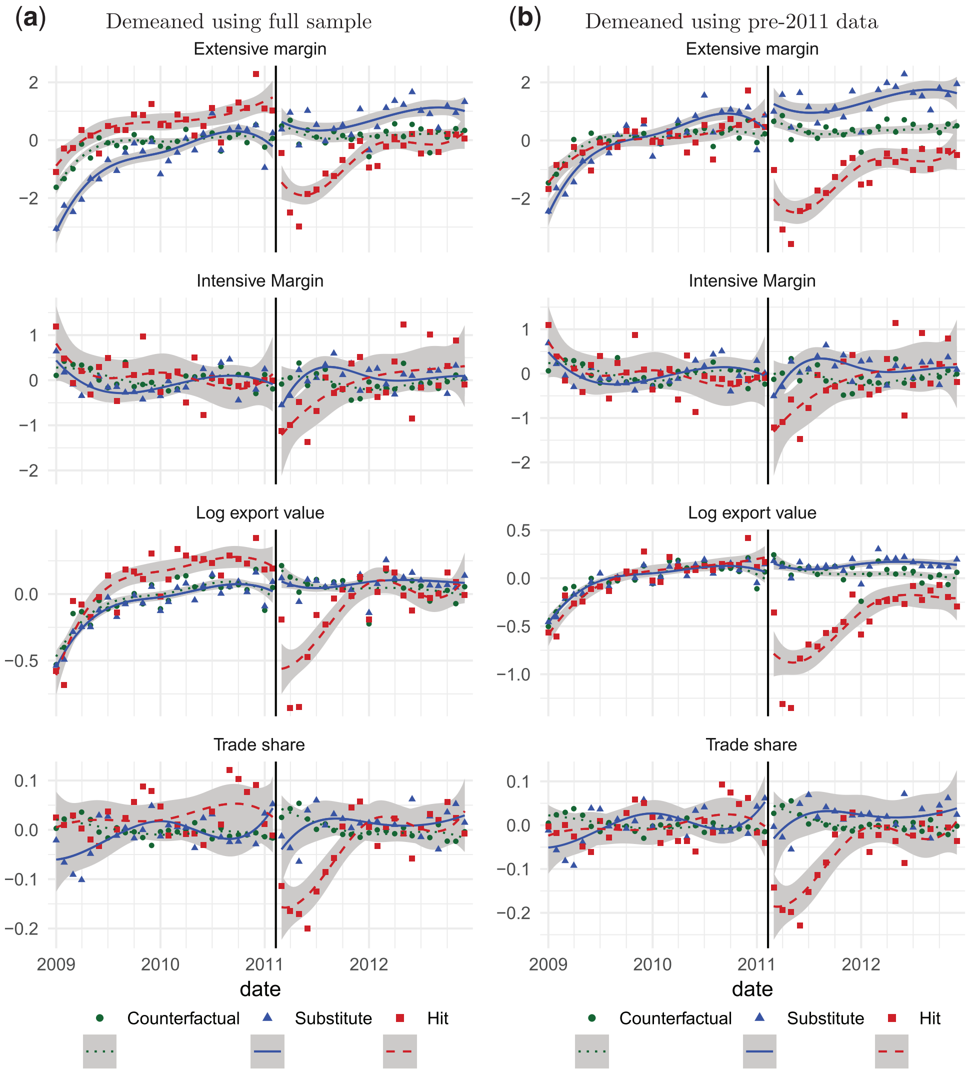

Figure 4. Average trade measures by port-group and time. (a) Demeaned using full sample and (b) demeaned using pre-2011 data.

Notes: The dots represent the average of the trade measures after demeaning at the port–sector level. The smooth line represents a polynomial fit based on all underlying sector–port observations. This polynomial is fitted separately for each port-group (counterfactual, substitute and tsunami hit) and period (pre- and post-tsunami). The shaded areas represent 95% confidence intervals. Panel (a) uses a demeaning procedure, where the means are based on the entire sample period. Panel (b) bases the means on the pre-tsunami period only. The vertical axes represent percentage points in the case of the EMs and IMs and trade share. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. For the interpretation of the IValue, the following adjustment is required, exp(scale) – 1. s.e. are not clustered in this representation.

3.3. Results

The estimation of regression (Equation 3.1.1) results in 48 coefficients for each outcome variable (24 months for tsunami-hit and substitute ports). Therefore, we present the coefficients graphically as a time plot, allowing to observe clear time-patterns.

Figure 5 presents the first results based on model (Equation 3.1.1). On the horizontal axes, time is indicated from January 2011 to December 2012. The vertical black line indicates the date of 11 March 2011. Since the monthly measures are plotted on the last day of the month, the first month in which the data should show an effect from the tsunami would be March 2011. The 95% confidence bands are based on clustered standard errors (c.s.e.) at the port level. In contrast to Figure 4, the results in Figure 5 aim to highlight the difference between the two types of treated ports relative to the counterfactuals. The plots allow for multiple comparisons, notably, at every point in time:

1. for tsunami-hit ports and substitutes ports relative to the counterfactual,
2. for each type over time, relative to the two months before the tsunami, and
3. tsunami-hit ports relative to substitutes ports. Each plot represents one regression and some additional statistics are indicated. The *F*-statistic is calculated as the difference between the estimated model and the projected model with no additional regressors.

While one can discern a time pattern in the various plots, we have not employed a smoothing technique or inter-month time dependence to gain some statistical efficiency from the time patterns. Every coefficient is calculated as the average difference relative to the counterfactual for a given month. The dramatic shock of the tsunami for the tsunami-hit ports is clearly visible. The drop is bigger for April 2011 relative to March as it accounts for the fact that exports were normal during the month until the earthquake of 11 March. The recovery took a few months, but there is a difference between the various measures. The EM and the IValue indicate the largest, statistically most significant and most persistent effects. While the IM and TS appear to recover within a few months, but indicate overall smaller absolute impacts. The larger impact on the EMs compared to the IMs and export value for hit ports is consistent with the theoretical model, which suggests that the product categories that disappear have a lower average export value.

Focusing on the substitute ports we note that the response is less dramatic relative to the fall of the tsunami-hit ports. This is not surprising overall. As indicated by the descriptive statistics, there are more substitute ports and each of these are on average larger relative to the tsunami-hit ports. We found the same pattern in the simulation of the theoretical model presented in Table 1. The substitution effect on an average substitution port will be smaller than the impact on an average hit port. Nonetheless, we find that the EM receives a significant boost at the same time as the tsunami-hit ports start to return to pre-tsunami levels from the summer of 2011 onward. For the IM, the response is much smaller overall and statistically indistinguishable from zero. For the log export value we find a significant increase, in particular from January 2012 onward. Finally, for the TS, we also find no statically significant effect.

The size of the effects can be read directly from the vertical axes. We can see for the EM a 6 percentage point decrease for the tsunami-hit ports, while there is a 2 percentage point increase for the substitutes at their respective peaks. Given the average EM of

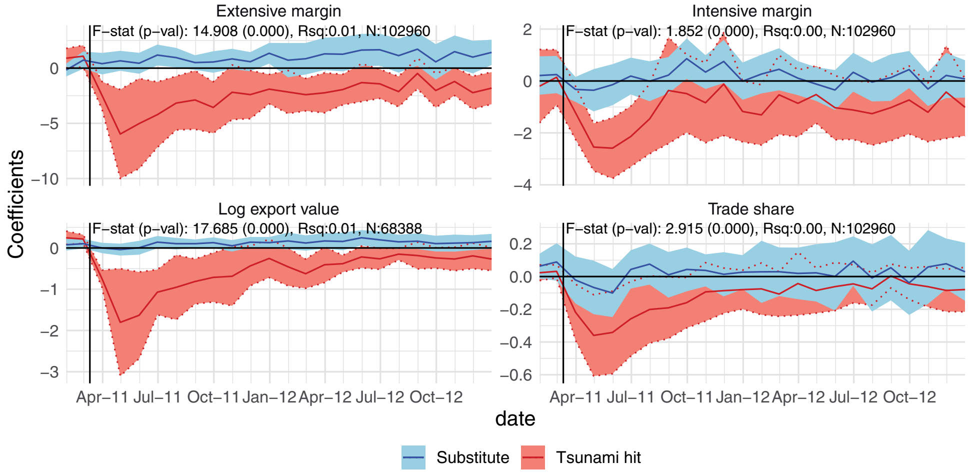

Figure 5. The effect of the tsunami relative to counterfactuals, model (Equation 3.1.1).
Notes: Each of the four plots present the coefficients of a regression of the corresponding trade margins on time dummies interacted with an indicator variable for tsunami hit and substitute ports as summarized in Equation (3.1.1). The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. The shaded area represents the 95% confidence interval using a clustered covariance matrix at the port level. The vertical line indicates the day of the Great East Japan Earthquake and tsunami, 11 March 2011. For each regression, some summary statistics of the regression estimation are indicated at the top of the plots.

tsunami-hit ports of 8.63 (see Table 2, EM section, column 'mean pre') for the tsunami-hit ports this means 69% ($= -5.97/8.63 \times 100$) decline. For the substitute ports the effect is smaller, presenting about a 7.0% ($=1.72/24.59 \times 100$) increase. The effect in percentage terms of the log export value can be read directly from the vertical axis. The plot indicates a dramatic drop in exports value for the first 2–3 months, which is not surprising, given the severity of the disaster. Despite the relatively quick recovery, the substitute ports gained around 28.1% ($= (e^{0.248} - 1) \times 100$) in additional exports on average at their peaks in May 2012. Using these estimates we can perform a back-of-the-envelope calculation to get an idea of the share of exports that was substituted to other ports. We find that on average at the port–sector level, for the period from March 2011 to February 2012, about 40% of exports was substituted to other ports.[14]

Figure 6 presents the cumulative effects of the four trade measures for 12 months from March 2011. The corresponding s.e. are calculated using the delta method. This figure makes it even more clear that the main export substitution effect goes through the EM. It also indicates the persistence of the shock, since the curves neither stabilize nor reverse to zero over time. The increasing confidence bands for the IM and TS indicate

---

[14] Using the statistics of log exports for substitute and tsunami hit in the pre-earthquake period from Table 2, and multiplying these with the summary statistics of the benchmark regression for log export value in Table 3, the calculation is, $(1.132 \times \exp(12.09))/(6.408 \times \exp(11.27)) = 0.401$.

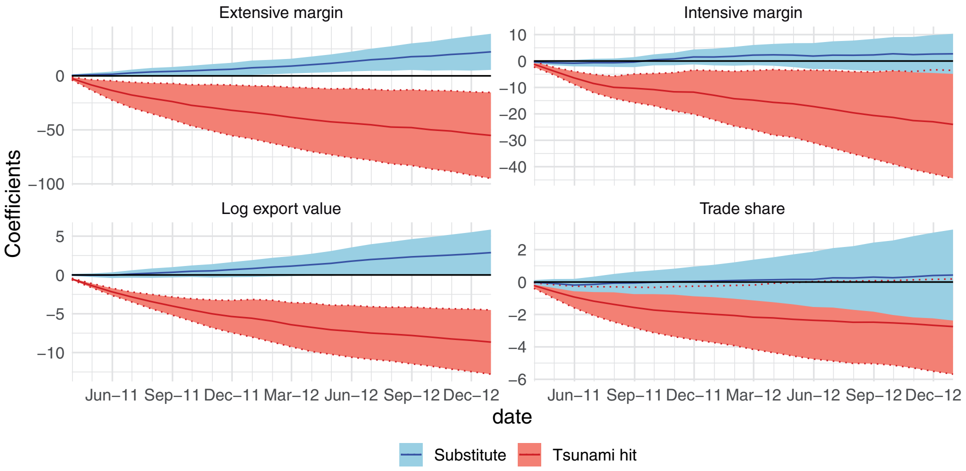

Figure 6. Cumulative effects.
Notes: Each of the four plots presents cumulative effects of the results presented in Figure 5. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. The shaded area represents the 95% confidence intervals calculated using the delta method.

that there is little correlations between the coefficients of subsequent periods, in contrast to the other two measures.

This cumulative measure also allows us to derive an informative summary measure that we can use to compare various estimation methods; we take the level of the effect at 12 months after the tsunami. In this way, we can compare models using a single statistic, which saves on plotting all the results. Table 3 presents results for slightly different specifications of our main model and the calculation of s.e., with many of the graphical representation available in Appendix B.4.1. The first four lines give the cumulative coefficients, $\sum \beta$, with the by-port-c.s.e. as presented in the figures above for the purpose of providing a benchmark against which to evaluate variations on our main specification.

The stars immediately to the right of the s.e. represent the statistical significance at the usual levels. The statistics indicate that for our benchmark model we have a statistically significant substitution effect for the EM and the IValue, but not for the IM and TS, in line with the graphical representations. The first few lines in the top panel only vary the calculation of the s.e. These variations do not alter our findings, but demonstrate that the clustering at the port level is a conservative strategy.

The sixth set of results present estimates where we estimate a version of model (Equation 3.1.1), but the fixed effects are replaced with left-hand-side variables that are demeaned at the port–sector levels using 2009–2010 data, as presented in Figure 4(b). Recall that the usual fixed effects absorb some of the actual impact of the shock, such that the benchmark estimates are conservative. We find indeed that the estimated point estimate has increased for substitute ports, and that this is in particular relevant for the EM and the log of exports value and their s.e.

Table 3. Summary robustness results

Model	Coef	Stat	EM	IM	lValue	TS
Benchmark model (Equation 3.1.1)	Hit	$\sum\beta$	−38.342	−14.786	−6.408	−2.171
		cse	14.180***	5.709***	1.449***	1.011**
	Sub	$\sum\beta$	9.043	2.235	1.132	0.121
		cse	3.471***	1.948	0.653*	0.639
Robust s.e.	Hit	rse	2.147***	2.601***	0.254***	0.198***
	Sub	rse	1.390***	1.463	0.231***	0.203
Cluster s.e. at region	Hit	cse	5.669***	1.313***	0.595***	0.197***
	Sub	cse	2.481***	1.304*	0.771	0.476
Cluster s.e. at prefecture	Hit	cse	15.183**	6.766**	1.445***	1.122*
	Sub	cse	3.189***	1.963	0.659*	0.594
Cluster s.e. at sector-year + sector-port	Hit	cse	6.220***	4.496***	0.686***	0.580***
	Sub	cse	2.644***	2.000	0.443**	0.433
Pre-differencing instead of FE	Hit	$\sum\beta$	−35.860	−15.216	−6.903	−2.034
		cse	14.077**	5.530***	1.560***	1.002**
	Sub	$\sum\beta$	12.355	1.585	1.376	0.207
		cse	3.022***	1.515	0.425***	0.582
$\alpha_{h,t} \times I(\text{elec.reg.}_\text{k})$ FE	Hit	$\sum\beta$	−36.249	−15.639	−6.339	−1.773
		cse	14.627**	6.135**	1.495***	1.080
	Sub	$\sum\beta$	9.705	1.726	1.238	0.266
		cse	3.391***	2.241	0.801	0.603
Exposure model (Equation 3.3.1)	Hit	$\sum\beta$	−5.508	−2.020	−1.442	−0.309
		cse	2.101***	0.997**	0.612**	0.156**
	Sub	$\sum\beta$	76.795	7.462	9.482	−2.095
		cse	40.246*	19.400	8.742	5.193
Robust s.e.	Hit	rse	0.305***	0.362***	0.090***	0.028***
	Sub	rse	12.633***	12.026	3.391***	2.042
Cluster at region	Hit	cse	0.145***	0.154***	0.070***	0.042***
	Sub	cse	20.336***	10.571	8.033	4.166

Notes: Statistics are the sum of the first 12 months from March 2011 onward. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. s.e. (cse for clustered and rse for robust) are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$. Benchmark estimated following (Equation 3.1.1) and Exposure following (Equation 3.3.1) with variations to the Benchmark and Exposure models as indicated. Clustering is at the port level unless otherwise indicated.
$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

Next, we use a different set of industry-time fixed effects, notably by interacting these with a port-specific electricity region indicator. This additional level of variation allows for differential industry trends for the two electricity regions of Japan (at 50 Hz in East Japan, while 60 Hz in West Japan with very limited interconnections). It may be possible that a large electricity disruption will be limited to one region. However, all nuclear plants were shut down after the breakdown of the Fukushima disaster, so essentially the electricity shock was nationwide (Economics of Energy & Environmental Policy, 2015). We find negligible changes in the summarized regression coefficients and the s.e. indicate that this does not alter our main findings.

The results in the bottom panel of Table 3 incorporate a measure for the heterogeneity of the size of the shock to the tsunami-hit and the substitute ports. Due to the variation in wave height as indicated in Figure 3, the damage to ports is heterogeneous. Most ports lost some berths, cranes, offices or storage facilities, but were not made entirely incapacitated (see Appendix B.3 based on Ono et al., 2016, for an indication of damage and recovery time of ports).

For the substitute ports, we can assume a function that approximates the potential exposure to additional exports from nearby ports. Here, we assume the following structure for the measure of $\text{exposure}_{gk} = \sum_{gl}\{\mathrm{I}(\text{hit}_l) \times \text{wave}_l/\text{dist}_{gk,gl}\}$. So for every sector-port *gk* in the set of substitute ports, we measure the road distance to all sector-ports *gl* that were hit by the tsunami. We assume that the effect diminishes with distance between ports. Using these measures we can augment model (Equation 3.1.1) to obtain

$$\begin{aligned} y_{gkt} = &\sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{hit},\tau} \cdot \mathrm{I}(v) \cdot \mathrm{I}(\text{hit}_k) \times \text{wave}_k + \\ &\sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{sub},\tau} \cdot \mathrm{I}(v) \cdot \mathrm{I}(\text{sub}_k) \times \text{exposure}_{gk} + \theta_{gk} + \alpha_{gt} + \epsilon_{gkt}. \end{aligned} \tag{3.3.1}$$

The cumulative effects are reported in the bottom panel of Table 3. Note that the interpretation for the coefficients now takes into account the unit of measurement, which for the tsunami-hit ports is in meters of the wave height and for the exposure of substitute ports in terms of wave height (m)/distance (10 s km) (using tens of kilometers scales the measures to comparable amplitudes). The median level of exposure across all sectors for substitution ports is 0.08. For illustration, Tokyo has as median exposure over all sectors of 0.15, and Fukui (on the northwest coast) has 0.06. So the average cumulative sectoral EM effect for these three values is the multiplication with the coefficient on substitution exposure as reported in Table 3 $0.08 \times 76.795 = 6.1$, $0.15 \times 76.795 = 11.5$ and $0.06 \times 76.795 = 4.6$, respectively, which is in line with the size of the coefficient presented for the benchmark, 9.043. The incorporation of heterogeneity in the regression increases the precision of the estimates of the tsunami-hit ports, but has little effect on the precision on the substitution ports.

3.4. Potential bias by plant destruction and plant substitution

We consider alternative specifications that aim to take explicitly account of the direct effect the disaster could have had on firms (Todo et al., 2015; Cole et al., 2017; Boehm et al., 2019). The earthquake should have damaged firms' plants themselves directly or induced the switching of production sites from damaged area to other safer locations. The first channel would cause an over-estimation of the effect on tsunami-hit ports, as the decline of exports is not solely due to the damage to ports but also due to the damage to firms. However, the trade substitution effect would be *underestimated* in our benchmark results, because declining production of firms would make it less likely to observe increased exports in substitution ports.

The second channel, the case of relocated production, could potentially increase production in an area close to a substitution port or counterfactual port. Assuming, for the sake of argument, that there was only a significant shift of production to areas where our substitute ports are located, then this could cause an increase of exports at substitution ports due to changes in production location rather than due to rerouting of goods from the original plant. This channel does not invalidate our claim that substitution took place, albeit that the mechanism is within firms/between plants, rather than through domestic routing choices. Moreover, this is a question of how we define the boundary of a firm, which is consistent with our theoretical framework.

We do not have firm-level data at a monthly frequency with information on shipments and port options, and to the best of our knowledge this does not exist for this period and the full range of sectors/products categories that we consider. However, prefecture level data of total industrial production at the monthly frequency is available. We incorporate this industrial production measure as control variable z_{gkt} in Equation (3.1.1). We add both the monthly aggregate industrial production for the prefecture in which a port is located, own prod.$\equiv$ log(production$_{kt}$), as the aggregate industrial production of the treated or non-treated region (excluding the production of a port's own prefecture), reg.prod. $\equiv$ log($\sum_{l=-k}$ production$_{lt}$). The coefficients on the two production variables indicate that production is positively correlated to trade, but, importantly, not statistically significant for log export value.

Interestingly, the point estimates of the cumulative effect for the hit and substitution ports have changed relative to the benchmark. Using the estimates that control for the potential decline in industrial production, the new estimates suggest an export substitution effect of 89%, which is more than double than the earlier result of 40%.[15] We provide further results on the interaction between industrial production and exports in Appendix B.4.5.

While we used prefecture level industrial production as additional controls in our regression, we like to gain further confidence that the substitution effect is mainly due to impact of the disaster on ports rather than on firms. First, Todo et al. (2015) and Cole et al. (2017), based on a survey of firms in the area, indicate that the vast majority of firms was operational within one month, while only a small minority was more severely affected up to the point where it could have entirely quit operations. Second, we calculated two measures using Geographical Information System (GIS) methods. One measure is based on building structures identified on OpenStreetMaps, and another is based on satellite land cover data. See Appendix B.2 for further details. Both measures give similar results, namely that in the Tohoku region around 5% of industrial and commercial land was affected by floods, while the relevant number for the Kanto region is much lower at 0.12–0.01% depending on the measure used. These numbers are again in line with the survey evidence of Todo et al. (2015) and Cole et al. (2017). We finally note that sector and country wide effects from the disaster are controlled for in our empirical specifications (3.1.1) and (3.3.1).

---

[15] Following the same calculation as before,

$$(2.005 \times \exp(12.09))/(5.143 \times \exp(11.27)) = 0.885.$$

Note, however, that the estimated coefficients for hit and sub may not be statistically different from each other between the two models. So while the point estimate for the substitution effect has roughly doubled, we should allow for some estimation uncertainty, between the two numbers, especially since the estimated coefficient on own prefecture and regional production is not statistically significant for log export value.

3.5. Differentiation by sector and destination

In line with the theoretical model we can empirically distinguish all effects by sector, h. In the theoretical model, the substitution effect is a function of the model parameters. Empirically, we do not observe the elasticity of substitution, σ_h, nor distribution parameter, κ, at the sector level and we also necessarily average out some of the trade costs shock between ports and the speed with which the shock subsides over time. Nevertheless, we can highlight the difference between sectors by estimating the effect for each sector separately (as if our β's are additionally subscripted by h). We calculated again the sum over the 12-month period from March 2011 onward. Table 5 presents results where each row represents a separate regression for the sectors where at least 9 of the 15 tsunami-hit ports had positive exports for each period from March 2011 to December 2012. The results are ordered descending by the EM of the substitute ports. What we find is that fresh and unprocessed sea products and high-tech products included in the optical/photography and machinery categories have the largest substitution effect. On the other extreme we find bulk industry goods and material that can likely be stored for an extended period. The order of the EMs for the hit ports does not show a similar pattern, but we note that the shock is represented among all sectors, in contrast to the substitution effect. In terms of the log export value, we find a negative shock among most sectors, but for the substitution effect we cannot detect a statistically significant effect for most sectors.

Todo et al. (2015) suggest that the supply chain may be critical especially for what they call the 'upstream manufacturing sector'. Freshness of products, given the unprocessed sea products, also appears to be a strong driver to divert products to other ports. In contrast, goods that can be easily stored, do not expire or perish quickly or are more costly to transport domestically are substituted the least. This intuitive relation between product characteristics and substitution supports the findings in the before mentioned studies that supply chains are important for the understanding of trade dynamics. Finally, the negative substitution effect of the EM of iron and steel could be further motivated from nationwide increased demand for the purpose of reconstruction efforts.

As a final exploration we look at the effects by destination regions (similarly as before, as if our β's are subscripted by j for destinations).[16] Note that the destination groups replace the sectoral definitions such that we calculate a single margin for each port-destination-month. If these destination groups can be seen as an approximation for the international trade costs and market size, then these estimations indicate whether destinations are affected differently by the disaster, even though this is not something we considered explicitly in the theoretical model.

Again we present the results in a table with the sum over the first 12 months from March 2011, see Table 6. These indicate that the substitution effect is the biggest for the closest markets, Asia, and Middle and South America. Therefore, international trade distance and market size appear to be the relevant driver of the size of the substitution effect given that these regions represent Japan's biggest export markets. The effect on Middle and South America in particular can be understood through the strong supply

---

[16] Following the Japanese trade statistics we group destinations over North America, Middle and South America, Asia, Western Europe, Central and Eastern Europe (incl. Russia), Middle East, Africa and Oceania.

Table 4. Prefecture production as control variables

Model	Coef	Stat	EM	IM	lValue	TS
Benchmark model (Equation 3.1.1)	Hit	$\sum\beta$	−38.342	−14.786	−6.408	−2.171
		cse	14.180∗∗∗	5.709∗∗∗	1.449∗∗∗	1.011∗∗
	Sub	$\sum\beta$	9.043	2.235	1.132	0.121
		cse	3.471∗∗∗	1.948	0.653∗	0.639
Benchmark with production	Hit	$\sum\beta$	−25.369	−12.936	−5.143	−1.159
		cse	10.200∗∗	5.747∗∗	1.272∗∗∗	0.889
	Sub	$\sum\beta$	11.137	3.072	2.005	−0.033
		cse	4.272∗∗∗	2.167	1.019∗∗	0.525
	Own prod.	$\sum\beta$	4.817	0.347	0.904	0.291
		cse	2.868∗	1.183	0.567	0.192
	Reg. prod.	$\sum\beta$	2.408	−0.513	0.782	0.297
		cse	4.913	1.697	0.778	0.512

Notes: Statistics are the sum of the first 12 months from March 2011 onward. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. c.s.e. at the port level are calculated using the delta method. For the log export value, coefficients were transformed using exp(β) − 1. Estimated following (Equation 3.1.1) and $z_{k,g,t} = \{\text{own prod}_{k,t}, \text{reg. prod}_{k,t}\}$.
$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

chain linkages between Japan and Mexico for the North American market. This aspect is demonstrated by Boehm et al. (2019). It suggest that the American market was prioritized in the port substitution to reduce as much as possible the disruptive effect on manufacturing output in this region. The other regions have both smaller coefficients which are statistically not different from zero at the usual significance levels. For Africa we even find a negative substitution effect.

3.6. Robustness

In Appendix B.4, we present further robustness results. First, one potential concern is that preexisting trends are driving our results. For instance, one might suspect that exports from ports in the Tokyo-Yokohama area were growing more strongly compared to those in the rest of the country and could therefore drive the substitution effect. Differential pre-trends were not visible in Figure 4, and we included industry-time fixed effects in the main specification. In Appendix B.4.2, we estimated the effect for each of the four Japanese treatment regions separately, including Hokkaido. These results indicate that the substitution effect is present in each region. Additionally, the Kanto area, which includes Tokyo-Yokohama, indicates the smallest substitution effect among the four regions and therefore appears to contribute the least to our estimated substitution effect. Since the available data start 2 years before the disaster, we are limited in estimating long-term trends. Second, in Appendix B.4.3, we vary the distance at which ports are assumed to be exposed to treatment, add Hokkaido as a treated region with hit and substitute ports and perform a placebo analysis by designating some of the counterfactual ports as substitute (while excluding substitute ports from the treated regions). All these function as a test on our selection of substitute ports and

Table 5. Differentiated effects over sectors

		EM		lValue	
Sector	Stat	Hit	Sub	Hit	Sub
Unprocessed fish and other sea products	$\sum\beta$	−113.291***	42.858*	−3.431***	4.258
	cse	29.041	22.756	0.732	4.919
Optical and photographic	$\sum\beta$	−3.882	38.687***	−3.909*	5.427
	cse	3.799	9.964	2.065	4.754
Machinery and mechanical appliances	$\sum\beta$	−34.556***	24.763***	−1.520	2.496
	cse	12.317	9.241	1.353	4.134
Products of stone and glass	$\sum\beta$	−34.257***	19.532*	−3.563***	5.572
	cse	8.938	9.978	1.127	3.812
Plastics	$\sum\beta$	−50.267***	18.522**	−7.506***	0.114
	cse	13.637	8.520	2.202	0.435
Electrical machinery and appliances	$\sum\beta$	−50.205***	16.485***	−2.357	−0.388
	cse	12.735	6.009	1.799	2.366
Other metals and articles thereof	$\sum\beta$	−46.987***	7.597	−8.326***	0.431
	cse	10.367	6.173	2.078	1.325
Articles of iron and steel	$\sum\beta$	−11.721***	6.701	−1.222	2.967
	cse	3.282	5.757	1.792	2.527
Other vehicles	$\sum\beta$	−19.499	4.878	−6.542**	1.754
	cse	31.102	22.842	3.008	2.975
Chemical products	$\sum\beta$	−47.021***	4.035	−9.247***	0.489
	cse	11.861	4.076	0.163	1.170
Paper and printed	$\sum\beta$	−52.613***	3.924	−8.385***	2.623
	cse	13.496	10.495	0.636	1.773
Processed agricultural products	$\sum\beta$	−33.316***	2.902	−3.397***	0.188
	cse	6.152	13.068	1.279	1.694
Other organic-based products	$\sum\beta$	−57.831***	1.867	−5.840***	−1.561
	cse	17.560	6.286	0.961	1.323
Other craft products	$\sum\beta$	−14.508***	1.472	−9.563***	0.314
	cse	2.504	7.825	1.268	1.505
Intermediate textiles	$\sum\beta$	−3.856**	−3.686	−8.240***	6.538
	cse	1.756	11.138	0.934	4.577
Iron and steel	$\sum\beta$	−10.459*	−5.538	−3.331***	1.949
	cse	6.273	6.186	1.041	2.040

Notes: Calculations based on model (Equation 3.1.1) for each sector separately. Statistics are the sum of the coefficients for the first 12 months from March 2011 onward. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. c.s.e. are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$.
$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

none of these results alter the conclusions we can draw from the main results. Third, we present additional results on measures of export values relative to prefecture production in Appendix B.4.5. The results indicate that the inclusion of production does slightly reduce the size of the substitution effect, but it does so without losing statistical significance. Fourth, we present results for an extended time span in Appendix B.4.4. We have also performed all the above analysis on the trade measures computed at the port level, rather than sector-port, with qualitatively similar results.

Table 6. Differentiated effects over destination regions

Region	Stat	EM Hit	 Sub	lValue Hit	 Sub
Middle and South America	$\sum\beta$	−30.490**	27.561***	−3.511***	1.464
	cse	13.429	5.176	0.862	1.136
Asia	$\sum\beta$	−29.899***	12.932***	−2.739***	2.408**
	cse	4.335	4.609	0.839	1.213
North America	$\sum\beta$	−11.287	9.140	−4.284***	3.636**
	cse	18.798	16.417	1.241	1.770
Western Europe	$\sum\beta$	−28.256***	6.395	−2.044**	2.363
	cse	8.539	8.061	0.931	1.657
Central and East Europe, incl. Russia	$\sum\beta$	−42.813**	6.229	−5.289***	0.990
	cse	16.996	8.135	0.831	1.679
Middle East	$\sum\beta$	−5.620	4.843	−4.812***	0.711
	cse	18.716	22.154	0.756	0.990
Oceania	$\sum\beta$	−23.174***	4.447	−4.989***	1.423
	cse	4.124	10.618	1.101	1.023
Africa	$\sum\beta$	−52.754***	−8.458	−3.265***	3.049**
	cse	6.817	14.926	1.183	1.298

Notes: Calculations based on model (Equation 3.1.1) for each destination region separately. ‘Groups’, g, are defined as country-destinations, where countries are grouped by the geographical region. Statistics are the sum of the coefficients for the first 12 months from March 2011 onward. The EM is the set of varieties exported from a port relative to the rest of Japan, weighted at total export value, the IM is the average export value for the varieties exported from a port and the TS is the total trade relative to rest of Japan. Mathematical expressions are provided in Appendix B.1. c.s.e. are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$.

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

4. Conclusion

In this article, we develop a new general equilibrium model with multiple ports and heterogeneous firms. Exporting requires local transportation costs and port specific fixed costs as well as international bilateral trade costs. Based on these two port specific costs, a port is characterized by its comparative advantage relative to other ports. Goods from firms will allocate over multiple ports in equilibrium in the presence of port comparative advantage. We then establish a gravity equation with multiple ports and show that gravity distortions due to heterogeneous firms are conditional on the existence of both internal variable and fixed trade costs. We show how exogenous variation in the transportation costs from firm to port and port specific fixed export costs induces a switch of exports from one port to the another, with the majority accounted for by changes in the product set (i.e. the EM of trade) despite it is smaller impact in terms of value added. We test the predictions of the model with Japanese customs data and find supportive evidence for a port substitution following the 2011 Great Japanese Earthquake. Back-of-the-envelope calculations suggest that at least 40% of exports were substituted to other ports. We also find substantial differences across product categories and destinations.

The findings in this article have implications for policymakers. With devastating storms and earthquakes striking regularly, disaster preparation is an issue across the world. We relate the recovery of economies after such events to the infrastructure available to firms, which allows for alternative options and routes used, whether domestically or internationally. With port-level export data, we focused specifically on the effect on international trade. We find that the port substitution effect is most evident for product varieties that are important in the supply chain networks of technology products, while products that are too bulky to transport domestically while storable for a longer period appear not to be substituted to other ports.

We demonstrate that exports can be substitute between ports in response to a natural disaster. While firms will have business continuity plans in place for such events, as shown by Cole et al. (2017), it is important to realize that they are dependent on the available infrastructure, including ports and roads. Therefore, policymakers should be aware of the mechanisms of port substitution after natural disasters when planning for regional and nationwide infrastructure projects (Akakura and Ono, 2017).

Inevitably we left some dimensions unexplored. Our empirical results indicate that the initial shock of the natural disaster has a diminishing impact over time. One could imagine that firms are forward-looking and anticipate the reconstruction and recovery phase, which introduces a dynamic aspect to the decision of firms to trade and incurring a fixed start-up cost of using a specific port. At the same time, our results indicate a persistent effect on substitution ports, even while some ports were completely reconstructed and operational within a few months. Large environmental disasters may therefore have persistent and long-term effects on the structure of the economy. Additionally, the heterogeneity of the substitution effect by sector and export destinations suggest that there is an interaction between supply chains and infrastructure. We leave these to future research.

Acknowledgements

This paper, under the former title “Adapting to within-country export barriers: Evidence from the Japan 2011 Tsunami”, was presented at Newcastle University (Newcastle, UK), Keio University (Tokyo, Japan), CEPII (Paris, France), Nagoya City University (Nagoya, Japan), Nihon University (Tokyo, Japan), University of Sydney (Sydney, Australia), McMaster University (Hamilton, Canada), Sophia University (Tokyo, Japan), Kyoto University (Kyoto, Japan) and the conferences of the Irish Economic Association, British Royal Economic Society, French National Economics Association, ITEA Conference and School and APTS in Hong Kong. We thank Brock D. Smith, Gerhard Toews, Gianluca Orefice, Svetlana Demidova, Kenji Ono, Yasuhiro Akakura, Toshihiro Okubo, Tomoya Mori and Se-il Mun for discussions and advice as well as seminar participants for helpful and constructive comments.

Funding

The present project was supported by JSPS KAKENHI Grant Number 18K01521.

References

Aerts, J. C. J. H., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., Kunreuther, H. (2018) Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, 8: 193–199.

Akakura, Y., Ono, K. (2017) Estimation method for port cargo demand after large-scale earthquakes and tsunamis. *Journal of the Japanese Society of Civil Engineers*, 5: 113–122.

Alessandria, G., Kaboski, J., Midrigan, V. (2013) Trade wedges, inventories, and international business cycles. *Journal of Monetary Economics*, 60: 1–20.

Ando, M., Kimura, F. (2012) How did the Japanese exports respond to two crises in the international production networks? The global financial crisis and the Great East Japan Earthquake. *Asian Economic Journal*, 26: 261–287.

Baldwin, R. (ed.) (2009) *The Great Trade Collapse: Causes, Consequences, and Prospects*. London: Center for Economic Policy Research.

Barrot, J. N., Sauvagnat, J. (2016) Input specificity and the propagation of idiosyncratic shocks in production networks. *Quarterly Journal of Economics*, 131: 1543–1592.

Belasen, A. R., Polachek, S. W. (2008) How hurricanes affect wages and employment in local labor markets. *American Economic Review: Papers & Proceedings*, 98: 49–53.

Bernard, A. B., Eaton, J., Jensen, J. B., Kortum, S. (2003) Plants and productivity in international trade. *American Economics Review*, 93: 1268–1290.

Bernard, A. B., Redding, S. J., Schott, P. K. (2010) Multiple-product firms and product switching. *American Economics Review*, 100: 70–97.

Boehm, C. E., Flaaen, A., Pandalai-Nayar, N. (2019) Input linkages and the transmission of shocks: firm-level evidence from the 2011 Tohoku earthquake. *Review of Economics and Statistics*, 101: 60–75.

Carvalho, V. M., Nirei, M., Saito, Y. U., Tahbaz-Salehi, A. (2016) Supply chain disruptions: evidence from the Great East Japan Earthquake. PRI Discussion Paper Series (No. 16A-15).

Cavallo, E., Noy, I. (2011) Natural disasters and the economy - a survey. *International Review of Environmental and Resource Economics*, 5: 63–102.

Chaney, T. (2008) Distorted gravity: the intensive and extensive margins of international trade. *American Economic Review*, 98: 1707–1721.

Clark, X., Dollar, D., Micco, A. (2004) Port efficientcy, maritime transport costs and bilateral trade. *Journal of Development Economics*, 75: 417–450.

Cole, M. A., Elliott, R. J., Okubo, T., Strobl, E. (2017) Pre-disaster planning and post-disaster aid: examining the impact of the Great East Japan Earthquake. *International Journal of Disaster Risk Reduction*, 21: 291–302.

Cole, M. A., Elliott, R. J. R., Okubo, T., Strobl, E. (2019) Natural disasters and spatial heterogeneity in damages: the birth, life and death of manufacturing plants. *Journal of Economic Geography*, 19: 373–408.

De Mel, S., McKenzie, D., Woodruff, C. (2011) Enterprise recovery following natural disasters. *The Economic Journal*, 122: 64–91.

Deryugina, T. (2017) The fiscal cost of hurricanes: disaster aid versus social insurance. *American Economic Journal: Economic Policy*, 9: 168–198.

Deryugina, T., Kawano, L., Levitt, S. (2017) The economic impact of hurricane Katrina on its victims: evidence from individual tax returns. *American Economic Journal: Applied Economics*, 10: 202–233.

Eaton, J., Kortum, S., Kramarz, F. (2004) *Dissecting Trade: Firms, Industries, and Export Destinations*. NBER Working Paper No. 10344.

Economics of Energy & Environmental Policy (2015) *Symposium on 'Japanese Energy Policy after Fukushima'*, vol. 5.

Feenstra, R. C., Ma, H. (2014) Trade facilitation and the extensive margins of exports. *Japanese Economic Review*, 65: 158–177.

Fomby, T., Ikeda, Y., Loayza, N. V. (2013) The growth aftermath of natural disasters. *Journal of Applied Econometrics*, 28: 412–434.

Gassebner, M., Keck, A., Teh, R. (2010) Shaken, not stirred: the impact of disasters on international trade. *International Economic Review*, 18: 351–368.

Gignoux, J., Menéndez, M. (2016) Benefit in the wake of disaster: long-run effects of earthquakes on welfare in rural Indonesia. *Journal of Development Economics*, 118: 26–44.

Hallstrom, D. G., Smith, V. K. (2005) Market responses to hurricanes. *Journal of Environmental Economics and Management*, 50: 541–561.

Head, K., Mayer, T. (2014) *Gravity Equations: Workhorse, Toolkit, and Cookbook, Volume 4 of Handbook of International Economics*, Chapter 3, pp. 131–195. Amsterdam, Netherlands: Elsevier.

Helpman, E., Melitz, M. J., Yeaple, S. R. (2004) Export versus FDI with heterogeneous firms. *American Economic Review*, 94: 300–316.

Hosono, K., Miyakawa, D., Uchino, T., Hazama, M., Ono, A., Uchida, H., Uesugi, I. (2016) Natural disasters, damage to banks, and firm investment. *International Economic Review*, 57: 1335–1370.

Hsu, P. H., Lee, H. H., Peng, S. C., Yi, L. (2018) Natural disasters, technology diversity, and operating performance. *Review of Economics and Statistics*, 100: 619–630.

Hummels, D., Klenow, P. J. (2005) The variety and quality of a nation's exports. *American Economic Review*, 95: 704–723.

Islam A., Nguyen C. (2018) Do networks matter after a natural disaster? A study of resource sharing within an informal network after cyclone Aila. *Journal of Environmental Economics and Management*, 90: 249–268.

Kahn, M. E. (2005) The death toll from natural disasters: the role of income, geography, and institutions. *The Review of Economics and Statistics*, 87: 271–284.

Kirchberger, M. (2017) Natural disasters and labor markets. *Journal of Development Economics*, 125: 40–58.

McIntosh, M. F. (2008) Measuring the labor market impacts of hurricane Katrina migration: evidence from Houston, Texas. *American Economic Review: Papers & Proceedings*, 98: 54–57.

Melitz, M. J. (2003) The impact of trade on intra-industry reallocations and aggregate industry productivity. *Econometrica*, 71: 1695–1725.

Ministry of Land, Infrastructure and Transport (2011) *Destruction of Port Facilities and Their Recovery after the Great East Japan Earthquake*. Report [In Japanese].

Nakajima, H., Koarai, M. (2011) Assessment of tsunami flood situation from the Great East Japan earthquake. *Bulletin of the GSI*, 59: 55–66.

Ono, K., Akakura, Y., Kaku, H., Ikeda, T. (2016) *Port Functions Continuing Management at the Large Scale Disaster-Theory and Practice for BCP*. Japan, Tokyo: The Ports and Harbours Association. [In Japanese, "Daikibo saigaizi no kowan kinou keizoku managment- BCP sakusei no riron to zissen", Nihon Kowan Kyokai].

Romalis, J. (2007) NAFTA's and CUSFTA's impact on international trade. *Review of Economics and Statistics*, 89: 416–435.

Sytsma, T. (2017) *The Impact of Climatic Disasters on Trade: Evidence from Hurricanes and US Ports*. Working Paper, University of Oregon.

Tanaka, A. (2015) The impact of natural disasters on plants' growth: evidence from the Great Hanshin-Awaji (Kobe) earthquake earthquake. *Regional Science and Urban Economics*, 50: 31–41.

Todo, Y., Nakajima, K., Matous, P. (2015) How do supply chain networks affect the resilience of firm to natural disasters? Evidence from the Great East Japan Earthquake. *Journal of Regional Science*, 55: 209–229.

Trepte, K., Rice, J. B. J. (2014) An initial exploration of port capacity bottlenecks in the USA port systems and the implications on resilience. *International Journal of Shipping and Transport Logistics*, 6: 339–355.

US Geological Survey (n.d.) Earthquake hazard program, significant earthquakes 2011. https://earthquake.usgs.gov/earthquakes/browse/significant.php [Accessed 21 February 2018].

Volpe Martinicus, C., Blyde, J. (2013) Shaky roads and trembling exports: assessing the trade effects of domestic infrastructure using a natural experiment. *Journal of International Economics*, 90: 148–161.

Zhu, L., Ito, K., Tomiura, E. (2016) Global sourcing in the wake of disaster: evidence from the Great East Japan earthquake. RIETI Discussion Paper Series 16-E-089.

Appendices

A. Theoretical appendix

A.1 Proof of Proposition 1

First, we look at the ranking condition of cutoff productivity levels. From Equation (2.4.1) and taking the ratio of ZPC of two ports k and l with $k > l$,

$$\left(\frac{\overline{\varphi}_{ijl}}{\overline{\varphi}_{ijk}}\right)^{\sigma-1} = \left(\frac{\mu_k}{\mu_l}\right)^{1-\sigma}\frac{f_{ijl}}{f_{ijk}}.$$

We have $\overline{\varphi}_{ijk} < \overline{\varphi}_{ijl}$ when $f_{ijl}/f_{ijk} > (\mu_{ijl}/\mu_{ijk})^{1-\sigma}$. Also dividing Equation (2.4.3) by profits for port l,

$$\left(\frac{\overline{\varphi}_{ijkl}}{\overline{\varphi}_{ijl}}\right)^{\sigma-1} = \frac{\mu_l^{-(\sigma-1)}}{\mu_l^{-(\sigma-1)} - \mu_k^{-(\sigma-1)}}\left(\frac{f_{ijl}-f_{ijk}}{f_{ijl}}\right) = \frac{1-\frac{f_{ijk}}{f_{ijl}}}{1-\left(\frac{\mu_k}{\mu_l}\right)^{1-\sigma}}$$

Thus, when $f_{ijl}/f_{ijk} > (\mu_{ijl}/\mu_{ijk})^{1-\sigma}$, we have $\overline{\varphi}_{ijl} < \overline{\varphi}_{ijkl}$ simultaneously.

Next, we look for the condition with which a marginal increase in productivity $\varphi^{\sigma-1}$ induces higher dividends for port l than port k. Namely,

$$\frac{\partial d_{ijl}(\varphi)}{\partial \varphi^{\sigma-1}} > \frac{\partial d_{ijk}(\varphi)}{\partial \varphi^{\sigma-1}} \tag{A.1}$$

From Equations (2.3.3) and (2.3.2), we can express profits in exporting from port k as

$$d_{ijk}(\varphi) = \frac{1}{\sigma}\left(\frac{\sigma}{\sigma-1}\frac{w_i\mu_k\tau_{ij}}{\varphi q_{ij}P_j}\right)^{1-\sigma}\alpha Y_j - f_{ijk}.$$

The similar expression holds for port l. Deriving these expressions with respect to $\varphi^{\sigma-1}$ for each port, we have $(\mu_k/\mu_l)^{\sigma-1} > 1$ so that Equation (A.1) holds. On the other hand, when $(\mu_k/\mu_l)^{\sigma-1} < 1$, for a marginal rise in productivity level, exporters prefer to export from port k. In such a case, all firms prefer to export from port k.

Finally, having established $C(K_n, 2)$ number of even profit cutoff productivity levels for any combination of two ports, provided the ranking of zero profit cutoff productivity levels for each port as Equation (2.4.2), the firm with φ eventually chooses to export from one specific port k^* that maximizes its exporting profits $d_{ijk^*}(\varphi)$, specifically by solving the following problem.

$$\max_{d_{ijk^*}(\varphi)}[d_{ijK_n}(\varphi), d_{ijK_n-1}(\varphi), \ldots, d_{ij2}(\varphi), d_{ij1}(\varphi)]$$

Together with the specific preference of firms with respect to exporting port as defined previously, the above condition establishes the Proposition 1.

A.2 Comparative statics

Here, we present the results of the comparative statics. Table A1 shows that shocks that are independent of port characteristics, namely τ, Z_i and q, have exactly the same impact on total exports from port H, X_H and those from port S, X_S, as well as for each margin. For instance, when bilateral trade costs τ rises, EMs decrease with the elasticity of $-\kappa$ while average export remains unchanged because of reduced IMs by $-(\sigma-1)$ but expanding export of surviving exporters by $\sigma-1$ (composition changes). The result is exactly the same for tsunami-hit port H and substitute port S. The same expression is provided by Chaney (2008) with a single port case.

As shown in Table A2, and mirrored in Table 1 in the main text, port specific shocks have dramatically different implications across ports. On the one hand, with respect to

Table A1. Additional comparative statics
(a) Margins decomposition[a]

Elasticities	EM	IM	CM	Total
$d\ln X_H/d\ln\tau$	$-\kappa$	$-(\sigma-1)$	$\sigma-1$	$-\kappa$
$d\ln X_H/d\ln q$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$d\ln X_H/d\ln Z$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$d\ln X_H/d\ln f_H$	$-\frac{\kappa}{\sigma-1}\mathsf{F}_H$	0	F_H	$-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_H$
$d\ln X_H/d\ln f_S$	$\frac{\kappa}{\sigma-1}\mathsf{F}_S$	0	$-\mathsf{F}_S$	$\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_S$
$d\ln X_H/d\ln\mu_H$	$-\kappa\cup_H$	$-(\sigma-1)$	$(\sigma-1)\cup_H$	$-[\kappa-(\sigma-1)]\cup_H-(\sigma-1)$
$d\ln X_H/d\ln\mu_S$	$\kappa\cup_S$	0	$-(\sigma-1)\cup_S$	$[\kappa-(\sigma-1)]\cup_S$
$d\ln X_S/d\ln\tau$	$-\kappa$	$-(\sigma-1)$	$\sigma-1$	$-\kappa$
$d\ln X_S/d\ln q$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$d\ln X_S/d\ln Z$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$d\ln X_S/d\ln f_S$	$-\frac{\kappa}{\sigma-1}\Gamma_S$	0	$-\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_S+\frac{\kappa}{\sigma-1}\Gamma_S<0$	$-\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_S$
$d\ln X_S/d\ln f_H$	$\frac{\kappa}{\sigma-1}\Gamma_H$	0	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H-\frac{\kappa}{\sigma-1}\Gamma_H>0$	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H$
$d\ln X_S/d\ln\mu_S$	$-\kappa\Theta_S$	$-(\sigma-1)$	$-[\kappa-(\sigma-1)]\bigwedge_S+\kappa\Theta_S<0$	$-[\kappa-(\sigma-1)]\bigwedge_S-(\sigma-1)$
$d\ln X_S/d\ln\mu_H$	$\kappa\Theta_H$	0	$[\kappa-(\sigma-1)]\bigwedge_H-\kappa\Theta_H>0$	$[\kappa-(\sigma-1)]\bigwedge_H$

[a] Trade effects by port, $k=H,\ S$, for various exogenous shocks: τ international trade costs q quality or demand shifter, f_k port specific fixed costs, μ_k port specific variable costs. The ports are differentiated by their relative fixed to variable cost of exporting. The decomposition of the total effect is given by EM, IM and CM.

(b) Parameters[b]

$$\bar{f}_H>0,\ \bar{f}_S>0,\ \overline{\mu}_H>0,\ \overline{\mu}_S>0 \qquad \bar{f}_H/\bar{f}_S>(\overline{\mu}_H/\overline{\mu}_S)^{\sigma-1}>1$$

$$\mathsf{F}_H=\frac{1}{1-\frac{\bar{f}_S}{\bar{f}_H}}>1 \qquad \mathsf{F}_S=\frac{1}{\frac{\bar{f}_H}{\bar{f}_S}-1}>0$$

$$\mathsf{F}_H>\cup_H=\frac{1}{1-\left(\frac{\overline{\mu}_H}{\overline{\mu}_S}\right)^{\sigma-1}}>1 \qquad \cup_S=\frac{1}{\left(\frac{\overline{\mu}_S}{\overline{\mu}_H}\right)^{\sigma-1}-1}>\mathsf{F}_S>0$$

$$\Gamma_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\cup_S}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\mathsf{F}_S}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>1 \qquad \Delta_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\cup_S}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\mathsf{F}_S}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>1$$

$$\Theta_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\cup_S}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\cup_S}{\left[\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1\right]}>1 \qquad \bigwedge_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\cup_S}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\cup_S}{\left[\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1\right]}>1$$

$$\Gamma_S>\Gamma_H=\frac{\mathsf{F}_H}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>0 \qquad \Delta_S>\Delta_H=\frac{\mathsf{F}_H}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$$

$$\Theta_S>\Theta_H=\frac{\cup_H}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>0 \qquad \bigwedge_S>\bigwedge_H=\frac{\cup_H}{\left(\frac{\cup_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$$

[b] The values $\bar{f}_H$, $\bar{f}_S$, $\overline{\mu}_H$ and $\overline{\mu}_S$ represent the steady state value of port specific fixed costs and local transportation costs.

trade flow X_H, when fixed export costs f_H increase, EMs decrease by $-\frac{\kappa}{\sigma-1}\mathsf{F}_H$ and CMs increase by F_H. This is because a number of less productive firms switch their use from the tsunami-hit port H to the substitute port δ following a rise in f_H. Total impact on export X_H is thus given by $-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_H$. Since $\mathsf{F}_H > 1$, both extensive and CMs are amplified compared to the results obtained in Chaney (2008) who find $-\frac{\kappa}{\sigma-1}$ and 1 for each extensive and CM, respectively, with a single port. On the other hand, for the same increase in f_H, EMs of substituting port S increase by $\frac{\kappa}{\sigma-1}\Gamma_H$ and CM increases by $\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H-\frac{\kappa}{\sigma-1}\Gamma_H$. As a result, total exports X_S increase by $\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H$. This is due to the above-mentioned port substitution effect through which some exporters switch from tsunami-hit port H to substitute port S in exporting following a rise in fixed export costs in tsunami-hit port H, f_H.

When local transportation costs to port H, μ_H, increase, exporters switch from tsunami-hit port H to substitute port S in exporting. As a result, total exports X_H decrease in tsunami-hit port H by $-[\kappa-(\sigma-1)]\cup_H-(\sigma-1)$ while total exports in substitute port S, X_S increase by $[\kappa-(\sigma-1)]\bigwedge_H$. In achieving such a change in X_H, the number of exporters decreases by $-\kappa\cup_H$, IMs decrease by $-(\sigma-1)$ while CMs increase by $(\sigma-1)\cup_H$ in tsunami-hit port H. We have a mirror image for each margin in competing substitute port S where total exports rise by $[\kappa-(\sigma-1)]\bigwedge_H$ through rise in EMs by $\kappa\Theta_H$ and changes in CMs by $[\kappa-(\sigma-1)]\bigwedge_H-\kappa\Theta_H$.

B. Empirical appendix

B.1 Additional statistics on ports

The trade data by custom-time-product-destination is available at http://www.customs.go.jp/toukei/info/tsdl_e.htm. The values are represented as F.O.B. Customs are located both at sea- and airports, we limit ourselves to seaports. Further information on the location of the ports was obtained from the website http://www.searates.com. Using the locations (GPS coordinates) bilateral distances were calculated using http://project-osrm.org. The median (min) distance between a substitute port and tsunami-hit port by region is as follows: Hokuriku 834 km (240 km), Kanto 541km (90 km), Tohoku 461 km (97 km) and Tokai 829 km (253 km). The same metrics for the nearest region with counterfactual ports, Kinki, are 1063 km (574 km).

Based on monthly custom-level export data, we calculate export value (by time, sector/destination grouping and port) and the empirical margins of trade following Hummels and Klenow (2005). Using k for each (Japanese) port with the set of all Japanese ports K, h for sector, j for destination, Ω for the product set with individual product code ω, and x for the export value, the margins are defined as,

$$\text{extensive margin}: \ EM_{hjk}=\frac{\sum_{\omega\in\Omega_{hjk}}\sum_{k\in K}x_{jk\omega}}{\sum_{k\in K}\sum_{\omega\in\Omega_{hjk}}x_{jk\omega}}\times 100,$$

$$\text{trade share}: \ TS_{hjk}=\frac{\sum_{\omega\in\Omega_{hj}}x_{jk\omega}}{\sum_{k\in K}\sum_{\omega\in\Omega_{hjk}}x_{jk\omega}}\times 100,$$

$$\text{intensive margin}: \ IM_{hjk}=TS_{hjk}/EM_{hjk}=\frac{\sum_{\omega\in\Omega_{hj}}x_{jk\omega}}{\sum_{\omega\in\Omega_{hjk}}\sum_{k\in K}x_{jk\omega}}\times 100.$$

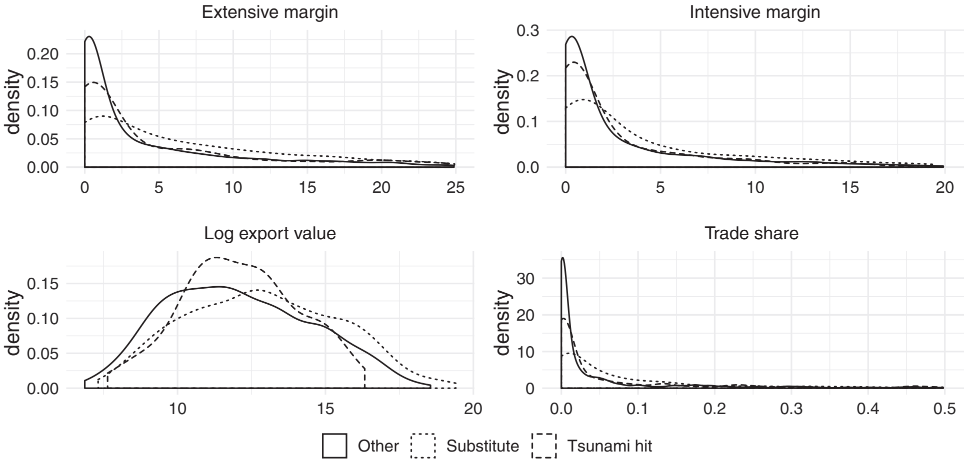

Figure B1. Density plot of port-level export measures by port group.

The margins are calculated for each month (*t*) independently. For instance, the EM for a particular sector–destination–port (*hjk*), we take the sum of exports over all ports for destination *j* and sector *h*, for the product set that is exported from port *k*, divided by the sum of exports over all ports for destination *j* and sector *h*. The empirical IM as defined here is the sum of the IM and compositional margin from the theoretical model. Destination *j* can be either the rest of the world or country specific, similarly, sector *h* can be represented at various levels of detail including the least disaggregated level of a single sector.

As we are looking for a substitution effect, we need to focus on those goods that were exported from ports that were hit by the tsunami. For this reason, we restrict the sample to all goods that had non-zero exports during the entire year of 2010 from at least one of the ports that were hit in March 2011. This restricted sample represents 77% in terms of the total Japanese export value in 2010. We drop ports that have less than 100 M (\approxUS1M) of exports in 2010. Furthermore, all ports will have each of the three margins for each sector in which they exported somewhere during the sample. So sector-level trade margins are included in all time periods, even if there are no exports recorded in certain time periods. The corresponding margins would then simply have the value zero. For the IValues, this creates a minor problem because the log of zero will create missing observations. This makes sure that we do not create a bias due to missing exports in tsunami-hit ports after the Tsunami, nor of missing sector exports pre-tsunami in substitute ports.

Figure B1 gives a representation of the distributions of the four key variables, grouped as tsunami-hit ports, substitutes and other. The plots are calculated using the average margins or values over 2009–2010 (i.e. pre-tsunami), without sector definitions. The density plots are calculated for each group separately, allowing to see the range of the available observations for each group. What is evident is that the substitute ports are relatively larger in terms of export value, and their extensive and IM.

Figure B2 indicates how the tsunami-hit and substitute ports rank relatively for each trade margin.

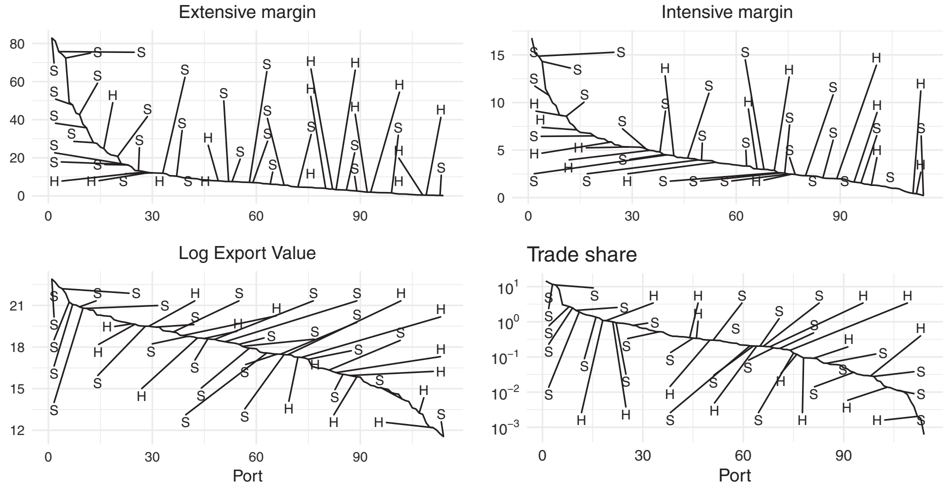

Figure B2. Ports ranked by trade measures (in 2010).
Notes: Distributions of trade margins over ports. 'H' indicate tsunami hit ports, 'S' indicate substitute ports.

There are 10 regions in Japan, of which four (Kanto, Tohoku, Hokuriku and Tokai) are considered 'treated' in our empirical setup. At the prefecture level, we have 39 (coastal) prefectures, 6 of these have one or more hit ports, 13 have one or more substitute ports. There are 116 ports, 15 were hit, 27 serve as substitute as noted in Table 2 with the Descriptive statistics. These numbers are also relevant for choice of clustering of our s.e. Clustering at the regional would relate specifically to the suspicion that ports within the same region will be supplied by firms that are similarly affected by the disaster and cause correlation between those firms, but not so when moving further away to other regions. However, the number of regions is relatively small. Therefore, clustering at the port or prefecture level would be more appropriate to avoid small-variance bias due to too few clusters.

Prefecture-level industrial production data comes from the Japanese Ministry of Economy, Trade and Industry, available at http://www.meti.go.jp/statistics/tyo/iip/chiiki/index.html. In the analysis, we use both 'own production', and 'regional production'. Own production always refers to the production of the prefecture in which the port is located. The variable regional production is for ports in the four treated regions (Tohoku, Kanto, Hokuriku and Tokai), it is the sum of all prefectures in this area minus the own prefecture production, for prefectures outside of those four regions the surrounding prefectures are the sum of all except regions except these four.

We use a dummy of the tsunami, or the height of the wave, as our independent variable in our specification rather than the damage incurred or the level of recovery over time for two reasons. First, we do not have comprehensive information on the damage to all ports. Second, both the damage (e.g. through the quality of wave defenses) and recovery are potentially endogenous to the local economic situation and port competitiveness. However, can provide an exogenous measure of damage based on reported wave heights, which are reported in Figure 3. For the substitute ports, we then combine the wave heights at the hit ports with the distance from substitute ports as presented in the main text.

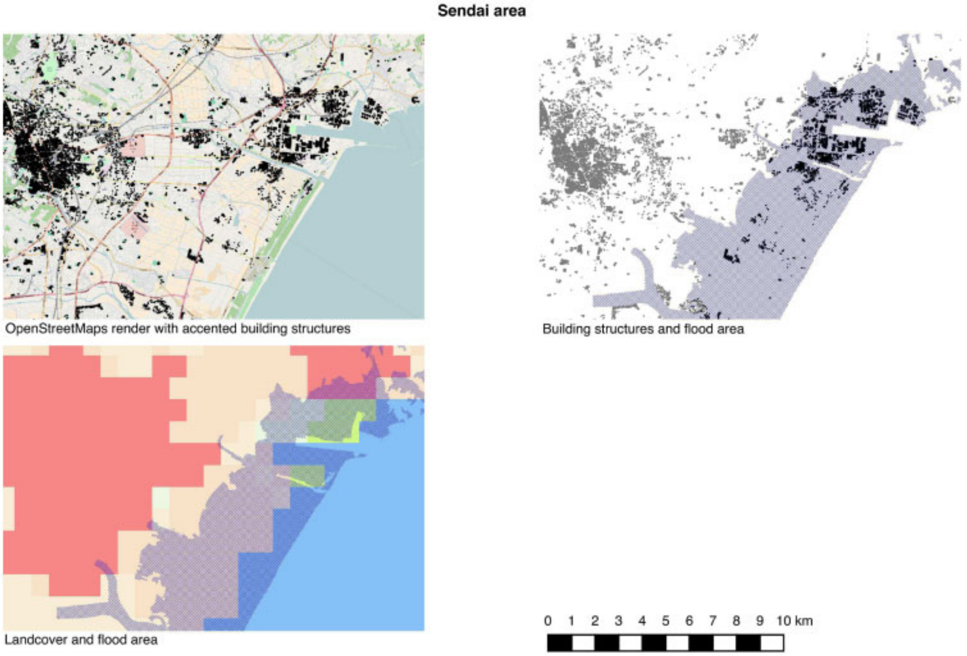

Figure B3. Measures of direct physical impact of the tsunami.

B.2 Direct flood impact

Todo et al. (2015) and Cole et al. (2017) use the same underlying dataset of firms in the ‘Special Great East Japan Earthquake Reconstruction Areas’, an area within the Tohoku and Kanto regions. In the sample of Todo et al. (2015), 5.7% of firms closed completely following the earthquake (p. 214), and 90% of the firms were operational within 30 days (p. 220), with a mean/median recovery time of 14.9/5 days (p. 215). In the sample of Cole et al. (2017), 1.55% of plants reported major earthquake damage, while 3.4% experienced major Tsunami damage (p. 6). They found a mean stoppage time of 16 days (p. 22).

We aim to further substantiate that the damage caused by the tsunami was limited to the coastal area but not the wider economy in the Tohoku and Kanto regions. We provide statistics on the affected region using two different datasets. Figure B3 gives an overview of the underlying data of the two approaches, around the Sendai-Shiogama port area, one of the worst-hit areas. We obtained a shapefiles of the flooded region from Geospatial Information Authority of Japan (GSI Japan, part of the Ministry of Land, Infrastructure, Tourism and Transport, Nakajima and Koarai, 2011). We spatially interacted these polygons with two data sources.

First, using OpenStreetMaps (OSM) we extracted all building structures in Tohoku and Kanto, and counted the number inside and outside the flood extend. The second panel showcases this method. The OSM data are from 2016, but it is impossible to exactly date all information contained. It is therefore possible that buildings that were destroyed and not rebuild are not in the dataset. In general, the building structures contained in the dataset are larger structures in city centers, industrial, commercial and military structures, but not residential housing. For our purpose of highlighting the effect on businesses, this might not be very problematic. We find that 0.12% of the buildings in Kanto, and 5.48% in Tohoku were flooded.

Second, we used a raster file on landcover from the GSI Japan (Global Map Japan version 1.1 Raster data, 2006), presented in Panel 3. Only one value of the raster band relates to build-up area, indicated as red cells. We calculated the total area of all cells that touch the flood region, independent of how much of the cell is covered by the flood region. We find that 0.01% in Kanto and 4.67% in Tohoku of build-up area was affected by the floods.

B.3 Port damage and port specialization

We establish in this section two features in the data. First, the damage done to ports was heterogeneous. Second, different ports have different specialization. We treat these features together because it helps to highlight the heterogeneity among ports in both treatment and individual characteristics.

The damage to ports was catalogued by the government for reconstruction purposes. Some Japanese literature on the disaster recovery strategies has used this data to indicate the heterogeneous effects on ports (Ono et al., 2016; Akakura and Ono, 2017). A summary of Figure 1 in Ono et al. (2016) is presented in Table B2.[17] The table indicates the number of berths for eight ports that were hit by the tsunami for three moments in time: before (initial), the number still functional right after, and those available after 520 days (about 17 months).[18] The data indicate the variation in size, heterogeneity in destruction and difference in recovery. The number of operational berths by port could give us a measure of damage or the size of the shock. While this would work for the initial time period, we prefer not to use this period as damage to

Table B2. Wave height and available berths over time, selected ports

Port	Prefecture	Wave height	Initial	t=20	t=510
Oofunato	Iwate	9.5	10	2	10
Sooma	Fukushima	8.9	13	3	4
Kamaishi	Iwate	8.1	7	3	7
Ishinomaki	Miyagi	7.7	31	12	30
Miyako	Iwate	7.3	26	7	26
Hachinohe	Aomori	6.2	44	22	44
Shiogama	Miyagi	6.0	42	11	40
Onahama	Fukushima	3.3	72	4	51

Notes: A selection of ports from the area affected by on the wave height from the Japanese Ministry of Land, Infrastructure and Transport (2011) and on the berth recovery from Ono et al. (2016), where '$t = 20$' and $t = 510$ indicate the days since the tsunami.

---

[17] We thank the authors for kindly providing the underlying data.

[18] The selection of ports in Ono et al. (2016) is slightly different, because we work at the level of the customs office. Therefore, we have a reduction in the ports that we can analyze here.

Table B3. Port specialization of tsunami hit ports, selected ports

Port	Prefecture	Agriculture (incl. fish)	Chemicals	Manufacturing (container)	Manufacturing (other)	Minerals
Oofunato	Iwate	8.4	0.2	88.4	2.9	0.0
Sooma	Fukushima	0.0	0.0	91.1	8.9	0.0
Kamaishi	Iwate	0.1	0.0	0.2	99.7	0.0
Ishinomaki	Miyagi	4.0	0.0	28.5	67.4	0.0
Miyako	Iwate	100.0	0.0	0.0	0.0	0.0
Hachinohe	Aomori	1.7	0.5	40.8	57.1	0.0
Shiogama	Miyagi	3.1	4.0	73.7	13.2	6.0
Onahama	Fukushima	0.3	7.6	74.4	17.4	0.3

ports as well as the recovery effort is surely endogenous to our outcome variable of export performance. Additionally, even if we would have full information on the berths for each port, including those not hit, different ports may have been affected differently, for instance through the destruction of cranes and other facilities. Therefore, the berths indicate only one aspect of port damage that need not be representative of the actual total damage incurred by each port. For this reason we believe an indicator variable of hit (and substitute) is an appropriate first approximation, and the (exogenous) height of the wave a good second.

As a second piece of heterogeneity we present for the same ports a breakdown by four sectors, which we believe correspond roughly to different modes of sea transport, agriculture and fish, minerals (for bulk transport), chemicals, manufactured articles (the bulk of container transport) and heavy or large manufactured items (other). We calculated the percentage of exports over these four categories in 2010 for each of these 11 ports. The results in Table B3 indicate that different ports have different specializations.

The two tables show the heterogeneity between ports, not only in size as indicated in Figures B1 and B2 but also by sectors that require different types of facilities. The damage done to ports was also heterogeneous, as was the recovery.

B.4 Additional regression results

B.4.1 Graphical representation of model (Equation 3.1.1) with alternative s.e. estimates

Figures B4–B10 relate to the set of results presented in Table 3.

For the pre-differenced estimation strategy as presented in Figure B8, our model can be summarized in a standard panel framework, where we use the conventional notation of cross-section index i, and time index t,

$$y_{i,t} = D'_{i,t}\beta + c_i + e_{i,t}.$$

The tsunami and substitution dummies are summarized in the column vector $D_{i,t}$, while c_i represent individual i (e.g. port × sector) unobserved time-constant effects. Therefore, c_i can be estimated using only data from before March 2011; $\bar{y}_i = c_i + v_i$, where

$\overline{y}_i = \frac{1}{26}\sum_{t=\text{Jan 2009}}^{\text{Feb 2011}} y_{i,t}$ and v_i the corresponding error. The variable D' is excluded from this equation since it contains no variation for the first 24 months in the sample. Subtracting, this equation from structural model, gives

$$\ddot{y}_{i,t} = D'_{i,t}\beta + \epsilon_{i,t},$$

where $\ddot{y}_{i,t} = y_{i,t} - \overline{y}_i$, and $\epsilon_{i,t}$ are the transformed model error. This procedure relies on the assumption that $\overline{y}_i$ is a consistent estimator of c_i. A fixed effects estimator would

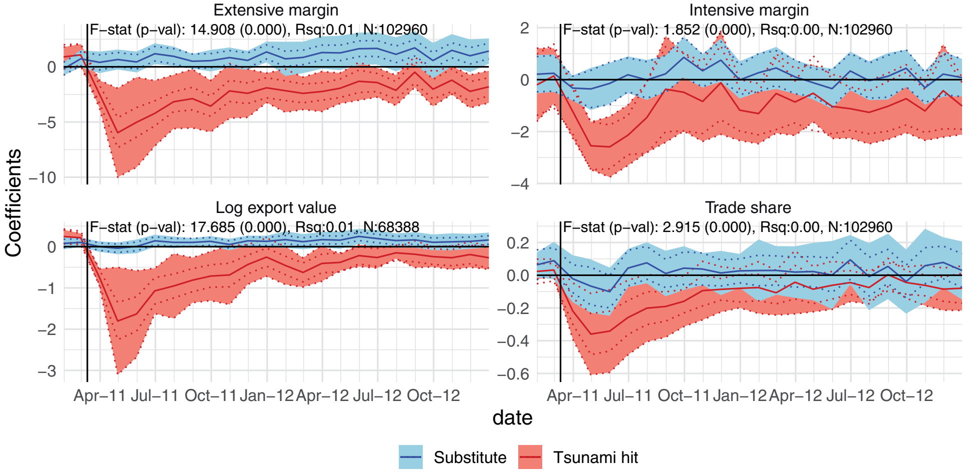

Figure B4. Overall margins of trade, model (Equation 3.1.1), with robust s.e.
Notes: Shaded area represent the 95% confidence interval using c.s.e. by port. The (inner) dotted lines indicate robust (white) s.e. See further the note of Figure 5.

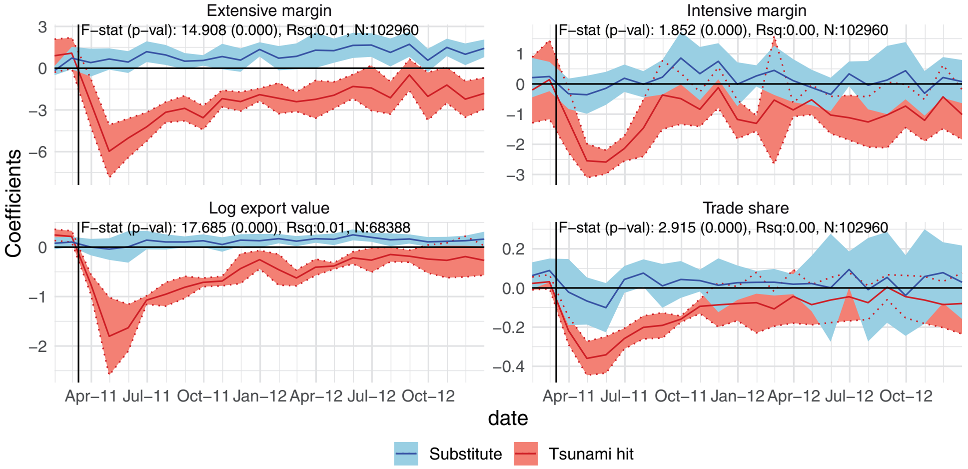

Figure B5. Overall margins of trade, model (Equation 3.1.1), c.s.e. by region.
Notes: The 95% confidence interval based on s.e. clustered by region. See further the note of Figure 5.

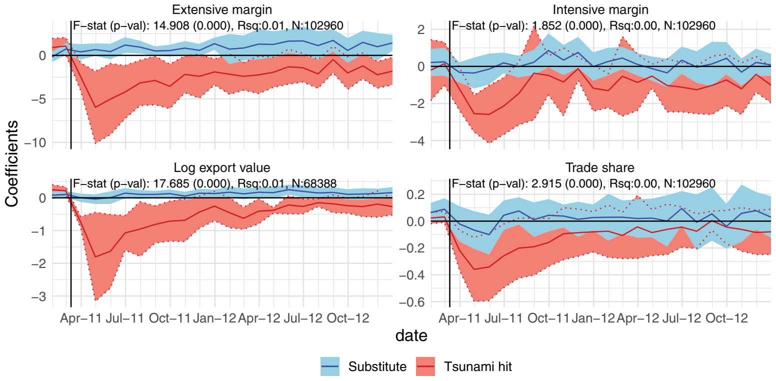

Figure B6. Overall margins of trade, model (Equation 3.1.1), c.s.e. by prefecture.
Notes: The 95% confidence interval based on s.e. clustered by prefecture. See further the note of Figure 5.

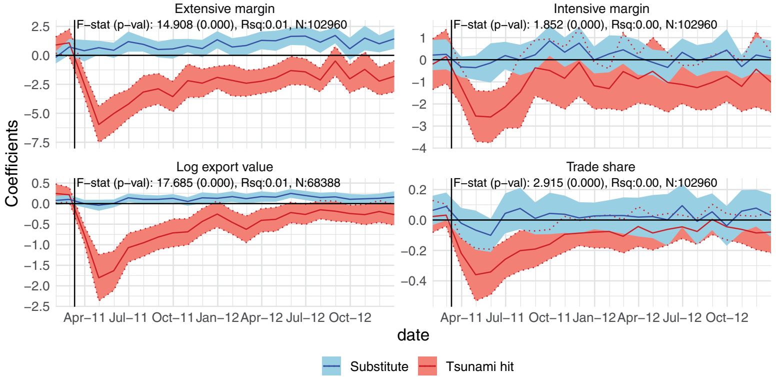

Figure B7. Overall margins of trade, model (Equation 3.1.1), c.s.e. by sector-year/sector-port.
Notes: The 95% confidence interval based on s.e. clustered by sector-year/sector-port. See further the note of Figure 5.

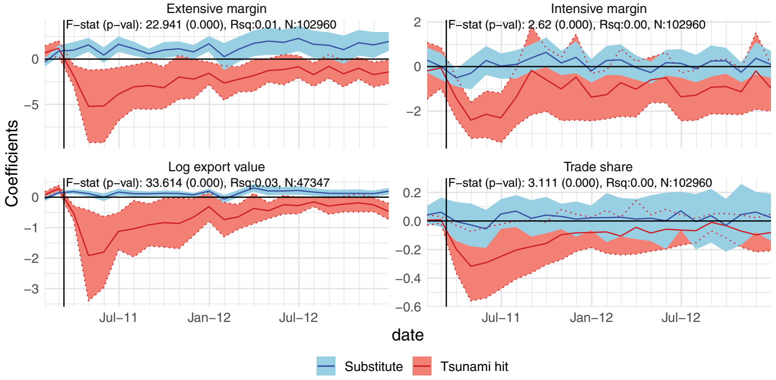

Figure B8. Overall margins of trade, model (Equation 3.1.1), pd transformation.
Notes: Estimation using pd variables instead of fixed effects transformation. See further the note of Figure 5.

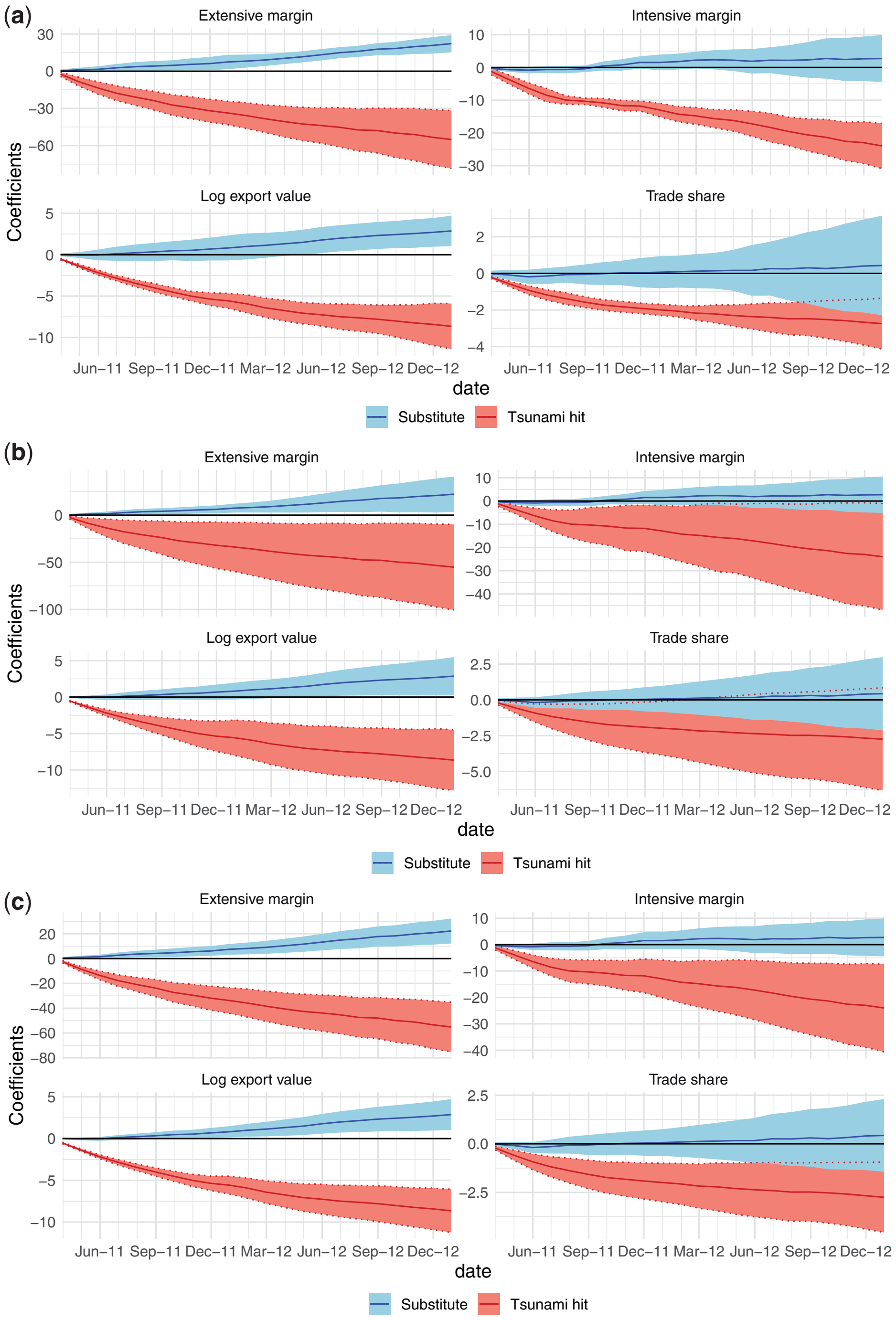

Figure B9. Cumulative effects. (a) s.e. clustered by region, (b) s.e. clustered by prefecture, and (c) s.e. clustered by port-year and port-sector.

Notes: Cumulative effects based on regressions presented in Figures B5–B7. Further see note of Figure 6.

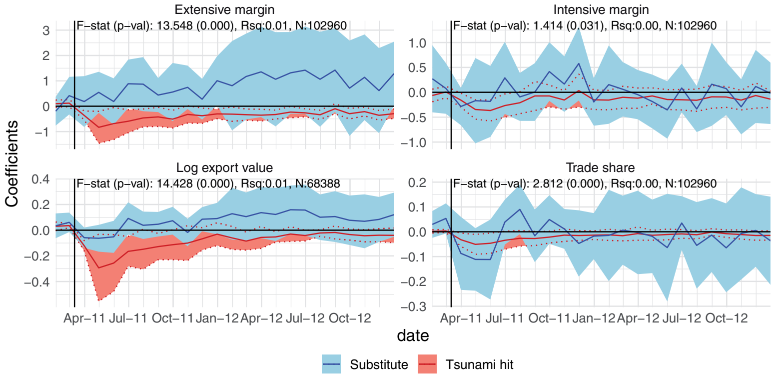

Figure B10. Overall margins of trade, model (3.3.1).

Notes: The vertical axes now takes into account the unit of measurement of the right-hand-side variables, which is wave height in meters for the tsunami-hit ports and the exposure measure as wave height/distance between ports (m/km) for the substitute ports. The coefficients for the latter have been scaled by 10 for readability. Further see note of Figure 5.

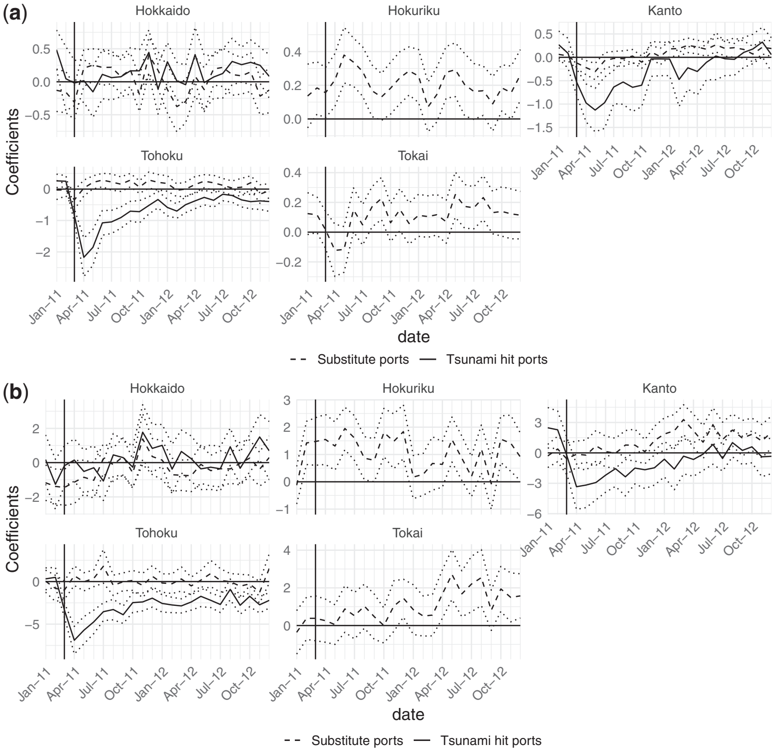

Figure B11. Results of log export value and EM by Japanese regions. (a) Log export value and (b) EM.

follow the same approach, but will use the *entire* time sample available including the period after March 2011 to estimate c_i. Alternatively, we could estimate the equation using 1-year differences. This would not be ideal in our case since the effect we are after can possibly be measured over a period longer than 1 year. For instance, we would not want to compare the impact in April 2012 against April 2011. Instead, we prefer to demean all effects from 2011 onward against the average port–sector level of the year 2009 and 2010 such that the estimated parameters show a difference-in-difference effect relative to the counterfactual ports.

B.4.2 By Japanese region

We estimated the effect for each of the four Japanese treatment regions separately, including Hokkaido. The results for Log export value are presented in Figure B11(a), for the extensive margin in Figure B11(b).

B.4.3 Varying substitute distance and selection

We present summary statistics of further robustness regressions in Table B4. Figures that belong to these regressions are available on request to the authors. The first three sets limit progressively the distance a port can be away from a tsunami-hit port to be able to function as substitute. In effect this limits the number of substitution ports as

Table B4. Summary robustness results

Model		Stat	EM	IM	lValue	TS
Exposure limited to 500 km	Hit	$\sum\beta$	−5.649***	−2.056**	−1.464**	−0.312**
		cse	2.107	0.996	0.611	0.156
	Sub	$\sum\beta$	65.089	−3.809	4.983	−4.862
		cse	51.129	22.784	8.795	6.325
Exposure limited to 300 km	Hit	$\sum\beta$	−5.682***	−2.066**	−1.473**	−0.317**
		cse	2.108	0.996	0.610	0.156
	Sub	$\sum\beta$	92.169	−15.121	2.604	−12.343
		cse	87.953	36.926	13.375	11.018
Exposure limited to 100 km	Hit	$\sum\beta$	−5.724***	−2.065**	−1.473**	−0.303*
		cse	2.112	0.995	0.609	0.156
	Sub	$\sum\beta$	337.193	−86.840	86.188	−5.088
		cse	356.685	178.965	659.299	23.801
Add Hokkaido as treated	Hit	$\sum\beta$	−24.603**	−4.618	−4.568**	−1.324*
		cse	11.402	5.947	1.774	0.766
	Sub	$\sum\beta$	7.267**	2.487	1.217*	0.144
		cse	3.260	1.784	0.647	0.562
Placebo analysis	Hit	$\sum\beta$	−25.677***	−4.672***	−6.574***	−1.347***
		bse	0.623	0.455	0.151	0.075
	Sub	$\sum\beta$	0.691	0.009	−0.017	−0.008
		bse	4.786	3.499	1.101	0.568

Notes: Statistics are the sum of the first 12 months from March 2011 onward. c.s.e. at the port level are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$. For the placebo analysis, the coeficient and s.e. represent the mean and standard deviation over 500 repetitions.

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

well as decreasing their level of exposure, while adding to the counterfactuals some ports that may be affected. What we see is that the coefficients on the substitution ports tend to increase the more we limit the distance range. This effect is due to the decreasing level of the exposure, which is compensated for through the increase of the coefficient. The second observation is that the trade margins for which we did not find a result thus far, the IM and the trade share become statistically significant in the more restricted settings. These results further underline the conservative nature of our main estimates.

The northern island Hokkaido is a special case. As a separate island with no road links (there is a train tunnel from Aomori, at the north of Honshu, to Hakodate on Hokkaido), it is unlikely that its ports are affected by a substitution effect from ports in Tohoku. Some ports of Hokkaido were exposed to the tsunami, but the recorded wave heights are minimal such that coastline barriers and storm protection may have proved sufficient to avoid severe damage. Adding Hokkaido as a treated region, rather designating its ports as counter-factual, changes little to our conclusions. Including Hokkaido increases the s.e. of the coefficients for each period, indicating that it does not serve well to identify the main effect we are after.

Finally, we performed a placebo analysis. We designate at random 10 ports from the counterfactuals as substitute, while removing all ports from the other regions that were not hit by the tsunami. We then estimate the same model. We repeat this 100 times. The results we present are the means and standard deviations of the estimated (12-month sum of) the coefficients over these 100 repetitions. The estimates for the placebo substitute ports should show little or no effect with no statistical significance, which is what we find.[19]

B.4.4 Extended time span

Figures B11 and B12 present results with longer time spans of the data. In contrast to the results presented in the main text we estimate the effect on the trade measures using a sample from 2009 to 2015, with parameters up to 2014. The results indicate that the substitution effect is persistent with little evidence of a return to pre-tsunami levels for log exports and the extensive margin of trade.

B.4.5 Prefecture-adjusted export value

We change our dependent variable to the ratio of exports over production:

$$\log(\text{export value}_{kht}/\text{production}_{\text{prefecture},t}).$$

For prefectures hit by the tsunami, the ratio will correct for the decrease in export, in particular when production drops at a rate similar to exports. For substitution prefectures, an increase in output would dampen the effect of the measures impact on exports.

While we have sector–port-level export data, we only have prefecture-level production data. We can aggregate the export data to the port or prefecture level to match the level of analysis. We present graphically the result of the cumulative impact of the

---

[19] The estimations for the tsunami-hit ports are not relevant since we do not change these ports over each repetition.

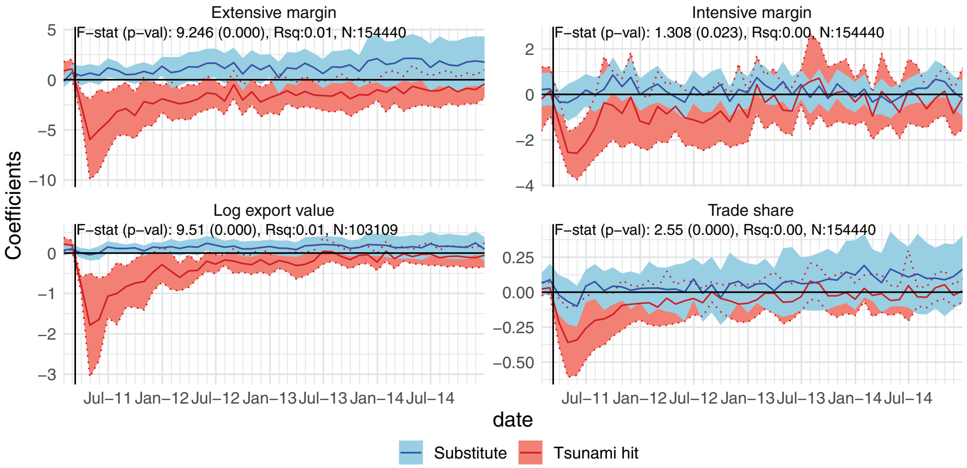

Figure B12. Overall margins of trade, model (Equation 3.1.1), with longer time span. *Notes:* Estimations based on sample from 2009 to 2015, with parameters estimated from 2011 to 2014. See further the note of Figure 5.

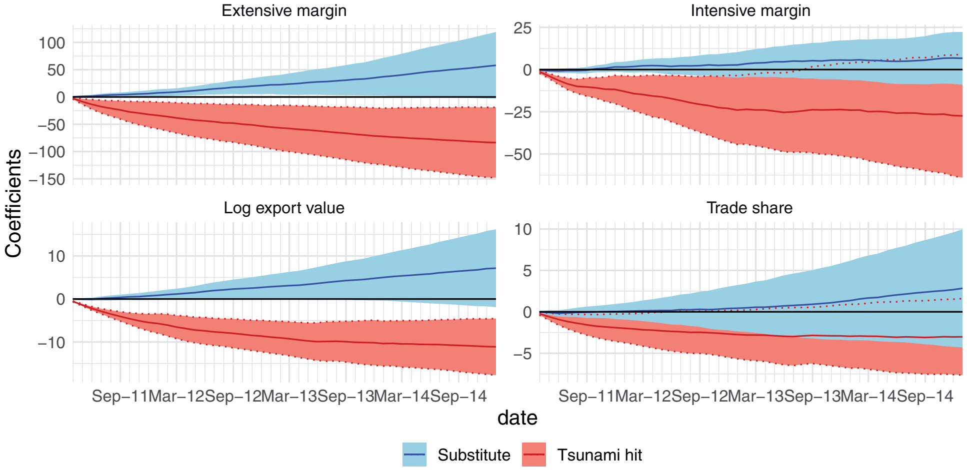

Figure B13. Overall margins of trade, model (Equation 3.1.1).
Notes: Estimations based on sample from 2009 to 2015, with parameters estimated from 2011 to 2014. See further the note of Figure 5.

disaster on exports and production at the prefecture level for exports and production in Figure B14.[20] Figure B14 indicates that there is some evidence for a decline in prefecture level production for those prefectures hit by the earthquake as indicated in the first panel. Noteworthy is also the slight increase of substitution prefectures, indicating that some output may have been transferred to those prefectures. However, when compared to the trade measure, and the trade-production measures, the effect of industrial output

---

[20] The loss of detail from a sectoral analysis will affect the precision of the estimates.

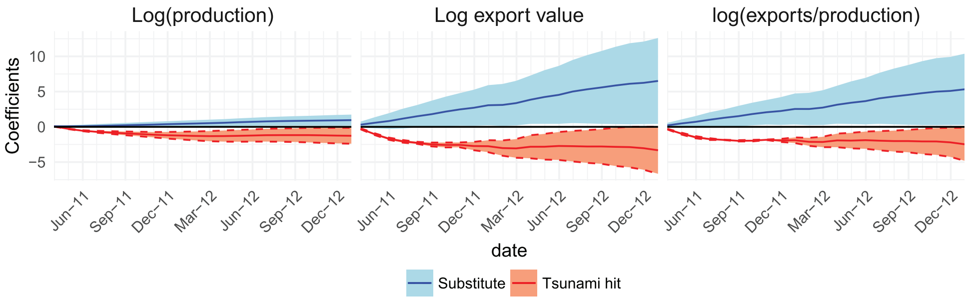

Figure B14. Cumulative impact with prefecture production.

Table B5. Summary robustness results

Data	Model		Stat	lValue	lValue/prod
2-digit sector—custom	fe	Hit	$\sum\beta$	−6.414***	−5.393***
			cse	1.458	1.456
		Sub	$\sum\beta$	1.203	1.526*
			cse	0.785	0.786
	pd	Hit	$\sum\beta$	−6.903***	−6.336***
			cse	1.528	1.429
		Sub	$\sum\beta$	1.514***	1.064***
			cse	0.479	0.407
Custom	fe	Hit	$\sum\beta$	−3.331	−1.743
			cse	2.401	2.566
		Sub	$\sum\beta$	2.063*	2.381**
			cse	1.194	1.177
	pd	Hit	$\sum\beta$	−3.966**	−3.170*
			cse	1.822	1.638
		Sub	$\sum\beta$	3.506***	3.058***
			cse	0.959	0.853
Prefecture	fe	Hit	$\sum\beta$	−4.681*	−3.378
			cse	2.400	2.607
		Sub	$\sum\beta$	1.559	1.872*
			cse	1.157	1.137
	pd	Hit	$\sum\beta$	−4.333**	−3.550*
			cse	1.937	1.824
		Sub	$\sum\beta$	3.327***	2.877***
			cse	1.026	0.915

Notes: Statistics are the sum of the first 12 Months from March 2011 onward. The estimates are repeated for log export value (lValue) and export value/prefecture industrial production (lValue/prod) at 2-digit sector-custom, custom and prefecture levels. c.s.e. the port level are calculated using the delta method. Coefficients were transformed using $\exp(\beta) - 1$. Estimated following (Equation 3.1.1), with fixed effects (fe) or pre-differencing (pd) as indicated.
$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$.

appears minimal relative to the direct impact on ports. This leads us to conclude that the effect of the disaster on the ports is the main driver of our results.

Table B5 presents the results for various level of aggregation of export given the prefecture level industrial production, using the fixed effects (fe) and pre-differenced (pd) specification. For fixed effects models, the inclusion of production increases the substitution effect, but for pre-differenced models it is decreased.

B.5 Definition of sectors

We aggregate various HS-2-digits together to create a more homogenous distribution on the number of product categories (n. var) in each sector. The results are given in Table B6. This also makes sure that most sectors are represented in most ports in most time periods.

Table B6. Sector definitions

HS code	HS name	n. var	New sector	New n. var
01	Live animals; animal products	14	Unprocessed animal and plants	265
02	Meat and edible meat offal	27		
04	Dairy produce; birds' eggs; na...	33		
05	Products of animal origin	14		
06	Live trees and other plants; b...	18		
07	Edible vegetables and certain...	51		
08	Edible fruit and nuts; peel of...	55		
09	Coffee, tea, maté and spices	40		
10	Cereals	13		
03	Fish and crustaceans, molluscs...	242	unprocessed fish and other sea products	242
11	Products of the milling indust...	24	Processed agricultural products	366
12	Oil seeds and oleaginous fruit...	42		
13	Lac; gums, resins and other ve...	9		
14	Vegetable plaiting materials; ...	5		
15	Animal or vegetable fats and o...	51		
16	Preparations of meat, of fish...	60		
17	Sugars and sugar confectionery	19		
18	Cocoa and cocoa preparations	11		
19	Preparations of cereals, flour...	21		
20	Preparations of vegetables, fr...	50		
21	Miscellaneous edible preparati...	20		
22	Beverages, spirits and vinegar	24		
23	Residues and waste from the fo...	20		
24	Tobacco and manufactured tobac...	10		
25	Salt; sulfur; earths and ston...	70	Solid minerals	167
26	Ores, slag and ash	34		
27	Mineral fuels, mineral oils an...	63		
28	Inorganic chemicals; organic o...	178	Inorganic chemicals	178
29	Organic chemicals	360	Organic chemicals	360
30	Pharmaceutical products	33	Chemical products	307
31	Fertilisers	21		
32	Tanning or dyeing extracts; ta...	53		
33	Essential oils and resinoids;...	31		
34	Soap, organic surface-active a...	23		
35	Albuminoidal substances; modif...	16		

(continued)

Table B6. Continued

HS code	HS name	n. var	New sector	New n. var
36	Explosives; pyrotechnic produc...	9		
37	Photographic or cinematographi...	38		
38	Miscellaneous chemical product...	83		
39	Plastics and articles thereof	188	Plastics	188
40	Rubber and articles thereof	87	Other organic-based products	280
41	Raw hides and skins(other than...	46		
42	Articles of leather; saddlery...	21		
43	Furskins and artificial fur; m...	10		
44	Wood and articles of wood; woo...	77		
45	Cork and articles of cork	7		
46	Manufactures of straw, of espa...	11		
47	Pulp of wood or of other fibro...	21		
48	Paper and paperboard; articles...	121	Paper and printed	140
49	Printed books, newspapers, pic...	19		
50	Silk	15	Textiles	491
51	Wool, fine or coarse animal ha...	41		
52	Cotton	168		
53	Other vegetable textile fibers...	23		
54	Man-made filaments; strip and...	133		
55	Man-made staple fibers	111		
56	Wadding, felt and nonwovens; s...	51	Intermediate textiles	205
57	Carpets and other textile floo...	21		
58	Special woven fabrics; tufted...	51		
59	Impregnated, coated, covered o...	25		
60	Knitted or crocheted fabrics	57		
61	Articles of apparel and clothi...	119	Final clothing and other worn products	340
62	Articles of apparel and clothi...	114		
63	Other made up textile articles...	53		
64	Footwear, gaiters and the like...	30		
65	Headgear and parts thereof	10		
66	Umbrella, sun umbrellas, walki...	6		
67	Prepared feathers and down and...	8		
68	Articles of stone, plaster, ce...	57	Products of stone and glass	224
69	Ceramic products	38		
70	Glass and glassware	66		
71	Natural or cultured pearls, pr...	63		
72	Iron and steel	416	Iron and steel	416
73	Articles of iron or steel	169	Articles of iron and steel	169
74	Copper and articles thereof	55	Other metals and articles thereof	313
75	Nickel and articles thereof	17		
76	Aluminum and articles thereof	41		
78	Lead and articles thereof	8		
79	Zinc and articles thereof	9		
80	Tin and articles thereof	6		
81	Other base metals; cermets; ar...	49		
82	Tools, implements, cutlery, sp...	88		
83	Miscellaneous articles of base...	40		
84	Nuclear reactors, boilers, mac...	662	Machinery and mechanical appliances	662
85	Electrical machinery and equip...	370	Electrical machinery and appliances	370
86	Railway or tramway locomotives...	22	Railway, aircraft and ships	54
88	Aircraft, spacecraft, and part...	14		

(continued)

Table B6. Continued

HS code	HS name	n. var	New sector	New n. var
89	Ships, boats and floating stru...	18		
87	Vehicles other than railway or...	144	Other vehicles	144
90	Optical, photographic, cinemat...	209	Optical and photographic	209
91	Clocks and watches and parts t...	52	Other craft products	240
92	Musical instruments; parts and...	19		
93	Arms and ammunition; parts and...	19		
94	Furniture; bedding, mattresses...	44		
95	Toys, games and sports requisi...	45		
96	Miscellaneous manufactured art...	54		
97	Works of art, collectors' piec...	7		