Adapting to within-country export barriers: Evidence from the Japan 2011 Tsunami*

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Abstract

How is a firm's ability to export affected by changes in domestic trade costs? We focus on 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 have a multiple port structure where exporting is subject to port specific local transportation costs and port specific fixed export costs as well as international bilateral trade costs. We derive a gravity equation with multiple ports and show that gravity distortion due to firm heterogeneity is conditional on port comparative advantage and resulting substitution of export across differentiated ports. We present evidence of the substitution effect using the 2011 Great East Japan Earthquake and following tsunami, which suggest that about 40% of the exports was substituted to other ports following the disaster, but mostly in sectors where goods are easily transportable and time dependent.

Keywords: firm heterogeneity, extensive margins, transportation costs, fixed costs, natural disasters.

JEL classification: F14, O18, R1

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1 Introduction

In this paper we investigate how exports respond to changes in the domestic trade costs. We do this in two ways. First, we develop a theoretical framework based on a trade model with heterogeneous firms and multiple ports between which a firm can choose to export. From a firm's perspective, each port will have a particular combination of fixed and variable cost. A profit maximizing firm will minimize the cost of exports. We derive the implications for international trade in the presence of multiple port structure. We hereby extend the gravity framework in heterogeneous firms model with internal trade costs and explicit interaction between domestic trade routes. Secondly, we test the predictions of the theoretical model with Japanese customs data, exploiting the Great Japanese Earthquake of 2011 as a natural experiment, to infer how goods bound for export markets were able to switch ports when domestic costs of exporting changed.

Trade cost includes fixed amount of investment such as search cost for finding trading partners and/or marketing cost for reaching customers (Arkolakis, 2010) as well as external shipment cost. These shipment costs also consist of domestic trade cost in carrying a specific product to a port and "implicit" costs that sellers of that product should pay once it arrives at the port. These implicit costs are the characteristics and features that allow a port to move the product to a ship destined for international markets. Ports are different in terms of their capacity, e.g. the number of ship they can handle within a day, facilities available to deal with different types of products, from containers to bulk cargo, the number of berths, transit space and warehouses. The efficiency of port administration and quarantine station to meet local standard in destination countries may also be a factor. Additionally, their natural condition in a bay, affecting the characteristics of breakwater and the ability of ships to enter and exit at any time.

These port features will be specific to different product categories. From a firm's perspective an efficient and large capacity port may, therefore, be preferable to a port located closer to the production side but lacking the same facilities. For instance, statistics from the Japanese Ministry of Land, Infrastructure and Transport, indicate that for 2008, of all agricultural, forest and fishery products produced in the Tohoku region, only 31.7% (in terms of weight) was shipped out through local port in that (Ministry of Land, Infrastructure, Transport and Tourism, 2009).

That ports and internal infrastructure specifically are important for the facilitation of trade is well understood (Clark et al., 2004; Feenstra and Ma, 2014). As external barriers to trade have fallen dramatically over the last decades, the interest in the role of domestic trade costs or internal barriers to trade has increased (Allen and Arkolakis, 2014; Coşar and Fajgelbaum, 2016; Ramondo et al., 2016). Policy makers interested in facilitating trade may make more progress by focusing on within-country barriers relative to those between countries. We focus in our study on the internal dynamics following changes to the costs of individual ports. As goods produced for exports are allocated over potentially many ports according to cost-minimization, changes in port infrastructure and capacities will affect this allocation, either by re-directing exports to other ports, or by cancelling the exports altogether.

Additionally, port substition has been recognised in civil engineering literature as crucial for the aftermath of natural disasters to limiting economic damage. Akaura and Ono (2017) note that port substitution took place during the 1995-Kobe earthquake, and the 2011 Great East Japan earthquake. Trepte and Rice (2014) indicate that the limited ability to substitute away from New Orleans based ports exacerbated the economic damage of Hurricane Katrina in 2005. Finally, from the perspective of a port authority, we can imagine competitive behavior between ports to attract goods by investing in port facilities and plant-to-port supply links.[1]

Starting from the above observation, we develop a model of multiple ports within countries based on Melitz (2003) and Chaney (2008). The number of ports in a country is exogenously given and ports from which heterogeneous firms export are differentiated with respect to their variable and fixed export costs. Given a firm's location, trade facilitation of each port depends on its comparative advantage between port specific local transportation costs and port specific fixed export costs. It is shown that exports are shipped through multiple ports in equilibrium as long as there exist such a comparative advantage structure.

In the presence of this port comparative advantage, we establish a port specific gravity equation. *Ceteris paribus* a rise in port specific variable and/or fixed trade costs decreases exports from that port while exports from the another competing port increases. As the port specific costs are expressed as a fraction of the goods shipped, the effect of substitution changes the aggregate flow of (after costs) exports as the costs structure of total exports changes when exports are directed from one port to another. Therefore, "internal" gravity matters for aggregate trade flow.

We test the prediction of cross-port substitution using Japanese port level export data. The 2011 Great East Japan Earthquake and following tsunami caused (Ono et al., 2016)an exogenous change in internal trade costs which affected some ports but not others. For each port we calculate measures of trade using monthly data of exports over 9-digit product categorizations and destination from 2009 onward. The earthquake and tsunami that followed damaged a number of ports on the north-eastern Honshu coast in the Tohoku region, especially those directly in the line of the Tsunami.Their facilities were damaged and rubble floating in the sea limited ships to enter or exit ports. For instance,

[1]For instance, there exist port competition within the European Union, where the internal borders have disappeared but ports may still be fiercely competing for trade and national governments can choose to invest in the infrastructure that facilitates trade through their national ports. See also the earlier mentioned Japanese government report (Ministry of Land, Infrastructure, Transport and Tourism, 2009).

among the main nine ports in Tohoku region, it took more than 250 days on average to recover 80% of berths). 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 one to two weeks (Cole et al., 2015a; Todo et al., 2015). Other ports, further away, especially in Keihin area (Chiba, Tokyo and Kanagawa) and the side of the Sea of Japan (Niigata and Hokuriku), were much less or not affected by the natural disaster and played a role of substitution ports for producers in the affected area. As the port counter-factual we use all other ports in Japan, who were far removed from the disaster region.

Our estimations indicate that for some months, substitution ports may have gained up to 30% additional trade and gained up to 2 percentage points in their extensive margin, representing a 7.3% increase from their pre-disaster margins. Overall, during the first 12 months after the earthquake, our estimates suggest that about 40% of the exports was substituted to other ports. However, we find large differences between sectors. Our results suggest that there are two key reasons that allow goods to be substituted. Firstly, there is an urgent need to do so, for instance due to pressures on timely supply chains or due to perishability of goods, and secondly the potential cost of transporting goods over land.

Although we do use a natural disaster for our identification strategy our focus is different from many studies in the literature on the economic consequences of natural disasters. Firstly, we are particularly interested in the effect of areas that were *not* hit by the disaster. Secondly, we argue that the damage was limited to the coast of north-eastern Honshu, and did not extend further inland. In a sense, the damage was specifically targeted at ports only.

Major earthquakes, such as one around Kobe in 1995, have been exploited to understand how such disasters propagate through an economy (Cole et al., 2015b; Hosono et al., 2012; Tanaka, 2015). First analysis on the 2011 Great Japanese Earthquake has come out, for instance with respect to the consequences on the energy market following the failure of the Fukushima-Dashi Nuclear power plant. A collection of research to the energy implications is presented in (Economics of Energy & Environmental Policy, 2015), while Coulomb and Zylberberg (2016) study the effect the disaster had on risk perceptions in the UK. Cavallo et al. (2014) studies product availability and prices in supermarkets. Zhu et al. (2016) studies the decision of off-shoring of Japanese firms in the aftermath of the disaster.

Closer to our work is Todo et al. (2015) who explore the role of local supply chain networks on firms recovery time after the 2011 earthquake using survey data. Cole et al. (2015a) investigate the role of pre-disaster planning on post-disaster firm level performance. These studies specifically note the relatively quick recovery of firms. However, the use of firm-level data implies some severe limitation due to the frequency of the observed data, which also limits their ability to deal with endogeneity issues. Using our monthly trade data we can closely follow the dynamics of recovery and substitution while controlling explicitly for pre-tsunami circumstances. Our limitation is that we must focus on ports rather than firms and, therefore, we complements these 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 network. They find no substitution effect in exports.

The paper is organized as follows. In Section 2 the theoretical model is presented and we derive the gravity equation with multiple ports. In Section 3, we present the results of our baseline regression analysis based on Japanese exports data from multiple regions. To allow differences by sectors we calibrate the theoretical model and provide a numerical simulation followed by further estimations in Section 3.5. Section 4 concludes.

2 The model

We start from a description of the theoretical model and explain the specific empirically motivated three-ports case, namely tsunami hit and substitute ports relative to an unaffected counter-factual, in the following subsection.

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 whose total number is exogenously given by K_n respectively. The country's total population and labour supply is also exogenously given by L_n. In each country, sector 0 provides homogeneous goods which serve as a *numéraire* and traded worldwide without any transportation cost while other sectors (whose total number is H) are made of differentiated goods. The port and sector are indexed by k and h, respectively. Each firm is heterogeneous in terms of their productivity level and monopolistically competitive.[2] In our model, firms choose a specific port for exporting.[3]

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 homogenous goods (omitting country

[2]For simplicity, we exclude the possibility of FDI and supply chain structure such as argued in Helpman et al. (2004)

[3]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.

specific subscripts for readability):

$$C = c_0^{\alpha_0} \prod_{h=1}^{H} \left(\int_{\Omega_h} \left(q\left(\omega\right) c\left(\omega\right) \right)^{1-\frac{1}{\sigma_h}} d\omega \right)^{\frac{\alpha_h}{1-\frac{1}{\sigma_h}}},$$

where c_0 is the consumption of homogenous goods. The consumption of a particular product variety, $c\left(\omega\right)$, is either produced locally or imported. The 'quality' of that good, $q\left(\omega\right)$, can be interpreted as an exogenous demand 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 α_0 and that on goods in sector h is given by α_h.

2.2 Ports and Firms

Firms in country i are assumed to be heterogeneous in terms of their specific labour productivity level, φ, and are facing the following choice: export or not export, and if export, a choice in ports. Production involves only labour 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 of local transportation costs within country, μ_k (> 1), as well as an iceberg type of bilateral trade costs, $\tau_{ij}(> 1)$.[4]

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

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

where w_i denotes real wages in country i which is found to be 1 due to our choice of *numéraire* and the level of labor productivity, Z_i, is common for all firms in country i. Figure 1 summarises the setting of our model. Since the mechanism of substitution is identical for each location-sector, from now on, we focus on firms in a specific sector and drop sector index h when there is no room for confusion.

2.3 Demand for differentiated goods

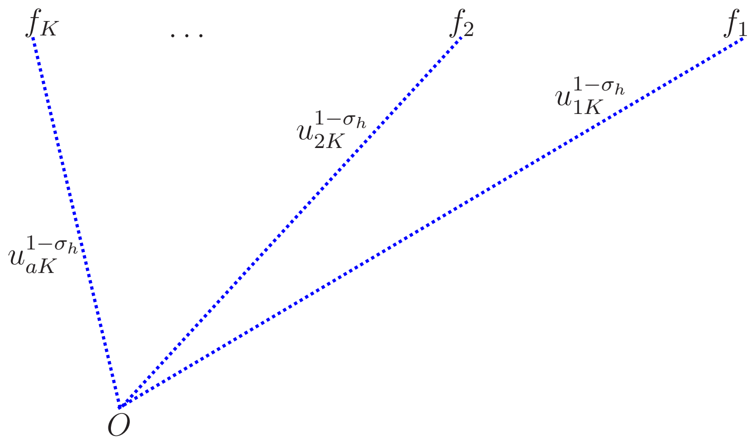
Due to the monopolistic competition, production scale is determined by demand. The demand addressed to the firm that has a productivity level φ from a destination country j is given by

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

with

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

Figure 1: Multiple Ports within country and sector h



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 firm located in O to port k, $\mu_k^{1-\sigma_h}$, varies by sector h through the sector specific elasticity of substition σ_h.

$$p_{ijk}(\varphi) = \frac{\sigma}{\sigma - 1} \frac{w_i \mu_k \tau_{ij}}{Z_i \varphi}. \tag{2}$$

In the above expression, P_j is the ideal price index for a particular sector in country j. The parameter q_{ij} is a origin-destination (-sector) specific demand shifter.

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 (1) and optimal price (2), we get

$$d_{ijk}(\varphi) = \frac{1}{\sigma} \left(\frac{p_{ijk}(\varphi) / q_{ij}}{P_j} \right)^{1-\sigma} \alpha Y_j - f_{ijk} \tag{3}$$

where Y_j is total income or total expenditure of country j, namely, $Y_j = P_j C_j = w_j L_j (1 + d)$ where d is 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 $d_{ijk}\left(\overline{\varphi}_{ijk}\right) = 0$ for each port. By solving the above zero-profit-cutoff (ZPC) condition, we have:

$$\overline{\varphi}_{ijk} = \lambda_1 \left(\frac{w_i \mu_k \tau_{ij}}{Z_i q_{ij} P_j} \right) \left(\frac{f_{ijk}}{Y_j} \right)^{\frac{1}{\sigma-1}}, \tag{4}$$

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_{ijk} and port specific fixed export costs f_{ijk}.

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

$$\overline{\varphi}_{ijK_n} < \overline{\varphi}_{ijK_n-1} < ... < \overline{\varphi}_{ij2} < \overline{\varphi}_{ij1}. \tag{5}$$

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. For any pair of cutoff productivity level $\overline{\varphi}_{ijk}$ and $\overline{\varphi}_{ijs}$ with $k = 2...K_n$ and $k > s$, we can further define another cutoff productivity level $\overline{\varphi}_{ijks}$ for which firms are indifferent in exporting from either port as $d_{ijk}(\overline{\varphi}_{ijks}) = d_{ijs}(\overline{\varphi}_{ijks})$. Solving this even-profit-cutoff condition (EPC), we have

$$\overline{\varphi}_{ijks} = \lambda_1 \left(\frac{w_i \tau_{ij}}{Z_i q_{ij} P_j}\right) \left[\frac{f_{ijs} - f_{ijk}}{Y_j \left(\mu_s^{-(\sigma-1)} - \mu_k^{-(\sigma-1)}\right)}\right]^{\frac{1}{\sigma-1}}. \tag{6}$$

Two competing ports k and s through their cutoff productivity level $\overline{\varphi}_{ijk}$ and $\overline{\varphi}_{ijs}$ have different port specific features with respect to local transportation costs and fixed export costs. This cut-off is meaningful in the following sense. Firms with productivity level $\overline{\varphi}_{ijks}$ will be indifferent between exporting through port k and s. For these firms, the relative variable costs and relative fixed costs exactly yield the same profit for the firm. To make this more concrete, we can say that one port, say s, 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 s, depending on their level of labour productivity φ, and therefore both ports will export some goods.

Formally, for firmsof sector h we can establish a *port comparative advantage* in the following proposition.

Proposition 1 .

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

Proof. See Appendix A.1. ■

When $(\mu_s/\mu_k)^{1-\sigma} > 1$, a marginal increase in profits of exporting from port s is higher than that from port k for firms with $\overline{\varphi}_{ijks} < \varphi$. Therefore, exporters spread into either port with which they earn higher exporting profits. Having established even-profit-cutoff productivity levels for any pairs of port provided by the ranking of zero profit cutoff productivity levels for each port as in (5), the firm with φ eventually chooses to export from one specific port k^* that maximises its exporting profits $d_{ijk^*}(\varphi_{ijlk})$. See also Figure 2 where we provide a specific case with $K_n = 3$ and $\overline{\varphi}_{32} < \overline{\varphi}_{31} < \overline{\varphi}_{21}$. Finally, note that the proposition 1 holds for each sector and firms' location.

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

Corollary 1 *When $\mu_1 > \mu_2 > ... > \mu_{K_n-1} > \mu_{K_n}$, 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. Finally, note that sector, country or destination specific characteristics (namely, σ_h, Z_i, q_j and τ_j) change the profitability of all concerning ports in a similar way.

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

$$\left(\frac{\sigma-1}{\sigma}P_j\right)^{1-\sigma} = \sum_{n=1}^{N} w_n L_n \left[\int_{\overline{\varphi}_{njK_n}}^{\overline{\varphi}_{njK_nK_n-1}} \left(\frac{w_n \mu_{K_n} \tau_{nj}}{Z_n q_{nj}}\right)^{1-\sigma} dG(\varphi) + \dots \right.$$
$$\left. + \int_{\overline{\varphi}_{nj21}}^{\infty} \left(\frac{w_n \mu_1 \tau_{nj}}{Z_n q_{nj}}\right)^{1-\sigma} dG(\varphi)\right] \quad (7)$$

2.5 Tsunami Hit and Substitute Port

We can now think of a structure of the model that fits our empirical strategy and data. 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.[5] Ports in group H are those hit by tsunami at the Great East Japan Earthquake. The 'tsunami hit' ports are mainly in Tohoku region.[6] Ports in group S are exposed to potential substitution of exporting from port H. The 'substitute' ports are hence in the neighboring area of Tohoku. Ports in group C are neither tsunami hit nor substitutes. These counterfactual ports are geographically far from Tohoku and neighboring areas.[7]

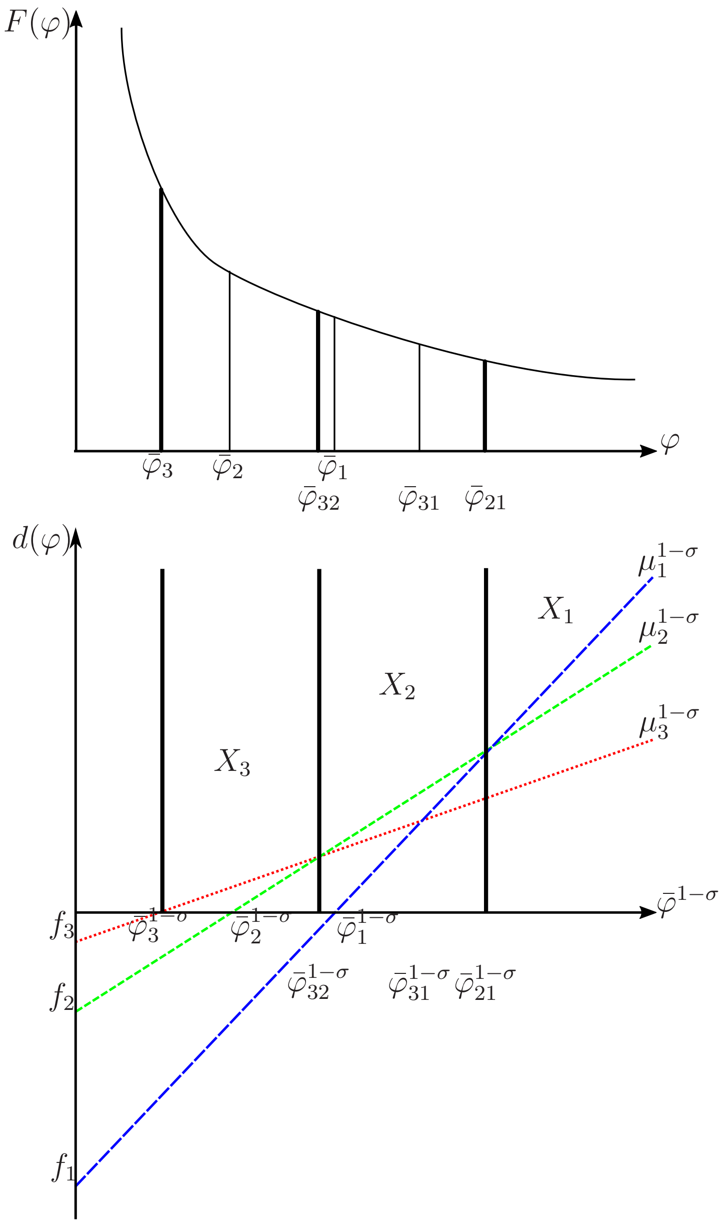
For the simplicity of the presentation, we assume three groups of ports structure with the rest of the world. To solve the model we assume the Pareto distribution for firm specific productivity level as $G(\varphi) = 1 - \varphi^{-\kappa}$ where κ ($> \sigma - 1$) is the shape parameter of the distribution. When κ increases, firms are more concentrated at its minimum level

[5]Tsunami hit ports H is not related to the sectors, nor are the counterfactuals C related to consumption.

[6]See the map of Figure 3 on page 19.

[7]It is possible to consider port substitution of firms located in other areas than Tohoku. Our empirical analysis does not exclude such possibility while it does not change the theoretical analysis.

Figure 2: Multiple Port in Action ($K_n = 3$ and $\overline{\varphi}_{32} < \overline{\varphi}_{31} < \overline{\varphi}_{21}$)



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 (lower panel). Each port offers a minimum level of productivity with which exports become profitable. For each combination of two ports there exists a level of productivity with which a firm would be indifferent between either port. Although the cut-offs between the two panels are aligned in the graph for ease of interpretation, the two panels have different horizontal scales.

of productivity, which we set as unity. Using the Pareto distribution and plugging the cutoff levels (4) and (6) in the ideal price index (7) 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 $\lambda_2 = [(1+d)/Y][\kappa - (\sigma-1)/\kappa][\sigma/(\sigma-1)]^{\kappa}(\sigma/\alpha)^{\frac{\kappa}{\sigma-1}-1}$ and

$$\vartheta_j^{-k} = \sum_{n=1}^{N} \frac{Y_n}{Y}\left(\frac{w_n \tau_{nj}}{Z_n q_{nj}}\right)^{-\kappa}\left[f_{njS}^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\mu_S^{-\kappa} + (f_{njH} - f_{njS})^{-\left(\frac{\kappa}{\sigma-1}-1\right)}\left(\mu_H^{-(\sigma-1)} - \mu_S^{-(\sigma-1)}\right)^{\frac{\kappa}{\sigma-1}}\right]. \tag{8}$$

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. 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, $x_{jk}(\varphi) = p_{jk}(\varphi)\, y_{jk}(\varphi)$ with $k = H$ or S, can be expressed as

$$\begin{aligned} x_{jH}(\varphi) &= \lambda_3 \left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i \mu_H \tau_{ij}}{Z_i q_{ij} \vartheta_j}\right)^{1-\sigma}\varphi^{\sigma-1}, \text{ if } \overline{\varphi}_{ijSH} < \varphi, \\ x_{ijS}(\varphi) &= \lambda_3 \left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\kappa}}\left(\frac{w_i \mu_S \tau_{ij}}{Z_i q_{ij} \vartheta_j}\right)^{1-\sigma}\varphi^{\sigma-1}, \text{ if } \overline{\varphi}_{ijS} < \varphi < \overline{\varphi}_{ijSH}, \\ &\quad 0 \text{ otherwise,} \end{aligned} \tag{9}$$

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

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

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

Finally we have $Y_j = (1+d)\, w_i L_i$ where d is constant.

2.6 Gravity

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

$$X_{ijH} = \alpha \frac{Y_i Y_j}{Y} \left(\frac{w_i \tau_{ij}}{Z_i q_{ij} \vartheta_j} \right)^{-\kappa} \mu_H^{-(\sigma-1)} \left(\mu_H^{-(\sigma-1)} - \mu_S^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}-1} \left(f_{ijH} - f_{ijS} \right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)}. \tag{10}$$

Exports from port S is given by

$$\begin{aligned} X_{ijS} = \alpha \frac{Y_i Y_j}{Y} \left(\frac{w_i \tau_{ij}}{Z_i q_{ij} \vartheta_j} \right)^{-\kappa} & \\ \left[\mu_S^{-\kappa} f_{ijS}^{-\left(\frac{\kappa}{\sigma-1}-1\right)} - \mu_S^{-(\sigma-1)} \left(\mu_H^{-(\sigma-1)} - \mu_S^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}-1} \left(f_{ijH} - f_{ijS} \right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)} \right]. & \end{aligned} \tag{11}$$

Total exports from country i to j is thus given by

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

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 $X_H = N_{XH} \widetilde{x}_H$ and $X_S = N_{XS} \widetilde{x}_S$ where $N_{XH} = wL\left(1 - G(\overline{\varphi}_{SH})\right)$ and $N_{XS} = wL\left(G(\overline{\varphi}_{SH}) - G(\overline{\varphi}_S)\right)$ represent the number exporters and

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

and

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

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.'

Table 1: Margins Decomposition

Elasticities	E.M.	I.M.	C.M.	Total
$\mathrm{d}\ln X_H/\mathrm{d}\ln f_H$	$-\frac{\kappa}{\sigma-1}\mathsf{F}_H$	0	F_H	$-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_H$
$\mathrm{d}\ln X_S/\mathrm{d}\ln f_H$	$\frac{\kappa}{\sigma-1}\Gamma_H$	0	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H-\frac{\kappa}{\sigma-1}\Gamma_H>0$	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H$
$\mathrm{d}\ln X_H/\mathrm{d}\ln \mu_H$	$-\kappa\mathsf{U}_H$	$-(\sigma-1)$	$(\sigma-1)\mathsf{U}_H$	$-\left[\kappa-(\sigma-1)\right]\mathsf{U}_H-(\sigma-1)$
$\mathrm{d}\ln X_S/\mathrm{d}\ln \mu_H$	$\kappa\Theta_H$	0	$\left[\kappa-(\sigma-1)\right]\Lambda_H-\kappa\Theta_H>0$	$\left[\kappa-(\sigma-1)\right]\Lambda_H$

Trade effects by port, $k=H, S$, for various exogenous shocks: 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 Extensive margin (E.M.), Intensive margin (I.M.) and Composition margin (C.M.). The definitions of the capital letters, F_H, Γ_H, U_H, Θ_H and Λ_H (all strictly positive) together with additional results on the comparative statics are given in Appendix A.2.

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,' 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 changes in iceberg type of bilateral trade costs τ, aggregate labor productivity level Z_i, country and destination specific demand shifter q, port specific fixed export costs f_k and port specific local transportation costs μ_k. Namely, we compute

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

where $k=H$ or S, $v=f_H$ or $\mu_H$and $d\ln\widetilde{x}_k/d\ln v$ includes both intensive margins and composition margins. Table 1 presents elasticities of each margin as well as of total exports with respect to each exogenous shock for each export from tsunami hit port H and substitute port S, respectively.[8] Capital letters in Table 1 are a function of parameters given these steady state values which are detailed in Table A-1b.

As shown in Table 1, port specific shocks have dramatically different implications across ports. On the one hand, with respect to trade flow X_H, when fixed export costs f_H increase, extensive margins decrease by $-\frac{\kappa}{\sigma-1}\mathsf{F}_H$ and composition margins 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 composition margins are amplified compared to the results obtained in Chaney (2008) who find $-\frac{\kappa}{\sigma-1}$ and 1 for each extensive and composition margin, respectively with a single port. On the other hand, for the same increase in f_H, extensive margins of substituting port S increase by $\frac{\kappa}{\sigma-1}\Gamma_H$ and composition margins 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.

[8]Results on comparative statics of changes in the trade margins from changes in Z_i, q, f_S and μ_S are presented in Appendix A.2.

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 $-[\kappa-(\sigma-1)]\,\mathsf{U}_H-(\sigma-1)$ while total exports in substitute port S, X_S increase by $[\kappa-(\sigma-1)]\,\Lambda_H$. In achieving such a change in X_H, the number of exporters decrease by $-\kappa\mathsf{U}_H$, intensive margins decrease by $-(\sigma-1)$ while composition margins increase by $(\sigma-1)\mathsf{U}_H$ in tsunami hit port H. We have a mirror image for each margin in competing substitute port S where total exports rise by $[\kappa-(\sigma-1)]\,\Lambda_H$ through rise in extensive margins by $\kappa\Theta_H$ and changes in composition margins by $[\kappa-(\sigma-1)]\,\Lambda_H-\kappa\Theta_H$.

3 Empirics

3.1 Empirical setup

We aim to estimate the size of the substituion of exports between ports using Japanese Trade data. We obtained monthly export statistics for the period Jan 2009 to Dec 2012, for each customs office in Japan with details on destination, value, quantity, at the 9-digit (6-digit HS codes with 3-digit Japanese specific addition) product level from the Japanese Ministry of Finance website, which is freely available.[9] The values are represented as F.O.B. Customs are located both at sea- and airports, we limit ourselves to seaports.[10]

We will exploit variation over time, ports, sectors and destination, and we only have one origin, Japan. Therefore we express the comparative statics as

$$\mathrm{d}\ln y_{k,h,t}=\text{constant}+a\cdot\mathrm{d}\ln\mu_{k,h,t}+b\cdot\mathrm{d}\ln\mu_{l,h,t}+c\cdot\mathrm{d}\ln f_{k,h,t}+d\cdot\mathrm{d}\ln f_{l,h,t},$$

where $y_{k,h,t}$ indicates the various trade margins, with subscripts as in the theoretical model, k and l for port, h for sector and t for time. The earthquake was an event that affected multiple ports. We view the event as a sudden increase in costs of those ports. With time ports were repaired and variable and fixed costs decreased again.[11] We can control for all other factors that determine 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 damage 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 towards the ports and the fixed cost associated with each port μ_k, μ_l, f_k and f_l (omitting subscripts i and j).

[9] Data available at http://www.customs.go.jp/toukei/info/tsdl_e.htm

[10] Further information on the location of the ports was obtained from the website http://www.searates.com

[11] Appendix B.3 gives an overview of some recovery time using data from <<AKAKURA REFERENCE>>

There is *a priori* no clear way to disentangle the variable from the fixed costs in our setup. On one hand infrastructure around ports and in some regions quite far inland was damaged or destroyed. In the immediate aftermath of the tsunami shortages in electricity or fuel may have been experienced by transporters. On the other hand, the damage of ports probably dominates the effect on port exports, because alternative roads could likely be used with very little additional costs and the destruction inland was less severe than at the coast line. Therefore we need to 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.

How does it matter for the research question? If we are interested in the effect of investments in port infrastructure on exports we naturally should include also the quality of transport links in a port's direct neighbourhood. In order to make the port function efficiently additional road and supply routes may be part of the port construction. Therefore, in the case of port construction one would also expect that the local transport costs and the port's fixed costs are affected simultaneously. Hence, what we are estimating is the average aggregate effect of such changes.[12]

Although the comparative statics of the theoretical model are such that positive and negative shocks have the same elasticity, we do admit that analysing port damage may not directly translate to answers on the effect of port upgrades. The destruction of ports does allow to look at the effect of major change in fixed costs that seems more suitable from an empirical point of view relative to a gradual and anticipated infrastructure development. Nevertheless, ports were rebuild after the disaster and we take that period into account. Therefore, together with the immediate impact of the disaster, we can analyse the two year reconstruction phase to give backing on the mechanism that we have in mind.

The model we will estimate is

$$\begin{aligned} y_{k,g,t} = & \sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{hit},v} \cdot \text{I}(v) \cdot \text{I}(\text{hit}_k) + \sum_{v=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{sub},v} \cdot \text{I}(v) \cdot \text{I}(\text{sub}_{k,g}) + \\ & \beta_z z_{k,g,t} + \theta_{k,g} + \alpha_{g,t} + \epsilon_{k,g,t} \qquad (12) \\ & k = 1, \ldots, 119; \; g = \text{sectors/destinations}; \; t = \text{Jan 2009,\ldots,Dec 2012} \end{aligned}$$

keeping with the notation of the theoretical model, k for port, g for group, such as sectors h or destinations m, and time t. Our main analysis will be done at the port-sector level, rather than port-destination, so in the following we will refer to sectors for exposition. The left-hand-side variable $y_{k,g,t}$ will be one of four trade variable of interest, log of export

[12] Additionally, we acknowledge that the tsunami damage and recovery period may have been perceived by some firms to be shock of a temporary nature, rather than a permanent change that would be more closely comparable to the construction of whole new ports or other infrastructure. A temporary shock may have allowed them to use inventory measures over the reconstruction phase, rather than re-route their goods to new ports, and therefore would reduce total exports. The use of inventory might be dependent on the specific categories of products and we find some evidence of this below.

value (lValue), extensive margin (EM), intensive margin (IM) and trade share (TS). The indicator functions $\mathrm{I}(\mathrm{hit}_k)$ and $\mathrm{I}(\mathrm{sub}_{k,g})$ designate those port-sector combinations that are treated by the tsunami or as substitute, which we discuss in the next subsection. For the tsunami-hit ports the indicator varies only at the port level since all products will be affected. However, for the substitute ports we assume treatment takes place at the port-sector level. For instance, only products belonging to the sectors that were exported from a tsunami-hit port will be treated as substitute, with others unaffected. 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 $z_{k,g,t}$ with corresponding coefficient β_z, such as prefecture level industrial production, further discussed below. The benchmark results will contain no control variables. Fixed effects are summarised by $\theta_{k,g}$ for the port-by-sector, and $\alpha_{g,t}$ for sector-by-time.[13] The first will capture port's specialization into certain sectors, the second will capture nation-wide sector development. For instance, the second would capture a nation-wide energy supply shock on (energy intensive) sectors following the earthquake. We note that in the case that certain sectors would be concentrated in the tsunami hit area this set of fixed effect could absorb some of the actual impact from the earthquake.

The parameters of interest are collected in the $\beta_{\mathrm{hit},v}$'s and $\beta_{\mathrm{sub},v}$'s, where v provides a separate label for each month. Given the reduced form structural equation above we have the following relationship between the parameters that we estimate and those that come from the theoretical model: $\beta_{\mathrm{hit},v} = a + c$ and $\beta_{\mathrm{sub},v} = b + d$. In combination with the indicator functions $\mathrm{I}(v)$ the estimated coefficients essentially indicate the evolution of the outcome variables over the 24 months time 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.

In line with the theory model we can empirically distinguish all effects by sector, h. However, the use of g in our empirical setup is more general than that, since we also know the destination of each product category from each port. So we can redefine g to denote (groups of) destinations, m, rather than sectors. The method of estimation remains unchanged. We will present results on both below.[14] Additionally we can let the $\beta_{\mathrm{hit},v}$'s and $\beta_{\mathrm{sub},v}$'s be varying over the group rather than estimating one average effect,

[13] These greek letters are not related to the ones in the theoretical model.

[14] The interaction of sector and destination is also possible in principle, but the 'bins' from which the margins would be calculated would become very small and potentially less reliable.

in effect subscripting the β's with g. We will present also these results.

We cluster standard errors at the regional level. This cluster-level 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.[15]

For our estimation to provide a valid measure of substitution we require two assumptions: Firstly, the shock should be exogenous with respect to the outcome variable. Secondly, the shock should be on ports rather than firms or the broader economy. We address these two points next.

3.1.1 Exogenous nature of tsunami to treated and control ports.

In terms of empirical identification we rely on the unexpected nature of the tsunami, which struck all ports at the same day. Although Japan is well adapted to the risk of earthquakes and the potential of tsunamis, the precise location, moment and magnitude of such events is for all practical purposes random, while the force of the Tsunami was unprecedented in modern times. This random occurrence of the tsunami makes that ports were randomly assigned this 'treatment'.

The tsunami was a devastating disaster for the coastal areas of the Tohoku and Kanto regions and around 16.000 people lost there lives. The earthquake had a magnitude of 9 on the Richter scale, the strongest recorded for Japan ever, with the epicentre 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 6 or higher. Multiple waves hit the shore of north eastern Honshu (Tohoku) with heights up to 6 meters from sea level. The force of the wave made the water surge inland as much as 40 meters 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). 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-Dachi 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. From the Japanese Ministry of Land, Infrastructure and Transport (2011) we have the recorded wave heights for each port. The ports closest to the earthquake epicentre were hit by the highest waves. This suggest that the damage to ports was heterogeneous. Indeed, most ports lost some berths, cranes, offices or storage facilities, but were not made entirely incapacitated (20 days after the disaster around 28%

[15]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 the Table 2 with the Descriptive Statistics.

of berths were operational, see Appendix B.3 based on Ono and Akakura, 2013).[16]

What is evident is that the ports hit by the tsunami are clustered in one region of Japan, Tohoku, and to a lesser extent Kanto. 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 find that ports in the Hokoriku and Tokai region may also have been close enough to be impacted. 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 the Tohoku region. 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.

Additionally, levels of potential substitution may be varying. Below we define a function that gives a measure of potential substitution for an individual port as the combined distance from tsunami hit ports and the height of the waves that these incurred. Intuitively, the color coding of the substitution ports (triangles) indicates that potential substitution may be stronger for ports in the Tohoku and Kanto regions relative to those in Hokuriku and Tokai.

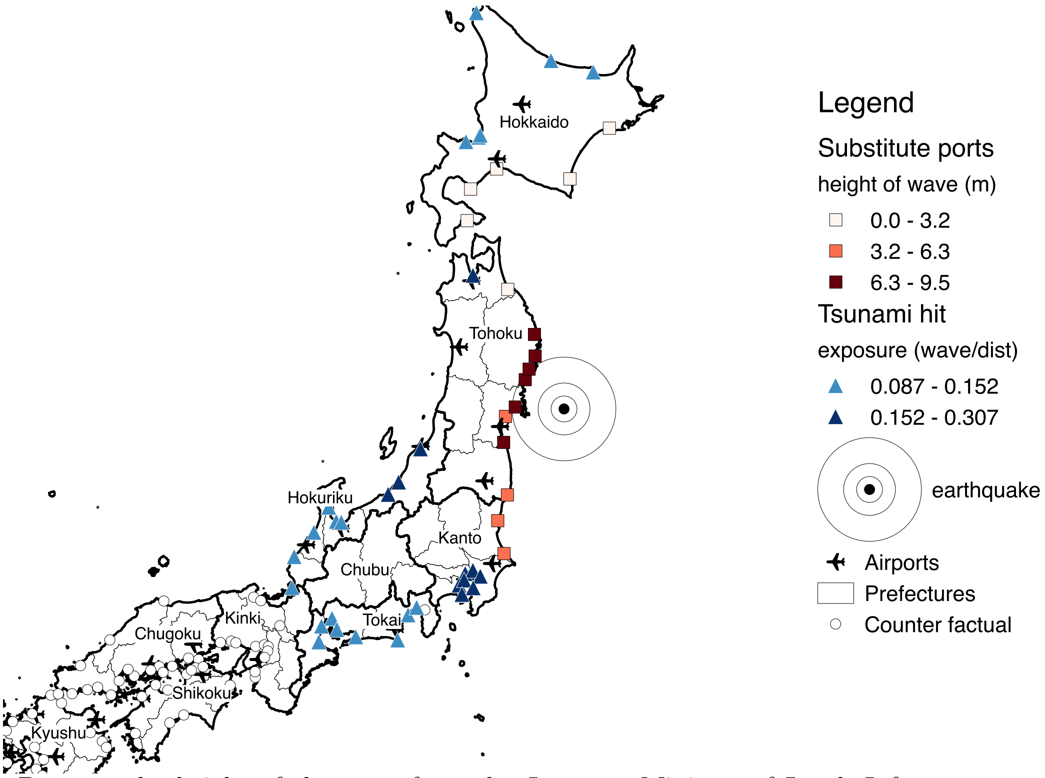
The ports further south-east in Japan, starting from the region of Kinki were likely too far away to be noticeable impacted and will henceforth be designated as the counterfactuals (circles). Since we found no effect of either hit ports or from substitutes in Hokkaido these ports are designated as counter-factual as well, but we change this designation in the robustness analysis.

3.1.2 Great East Japan Earthquake and evidence on firms

Although devastating we argue that the damage from the earthquake and tsunami was largely limited to the immediate coastline rather then the hinterlands, as well as limited to the coastline closest to the epicentre and so would have limited direct effects on local business further inland and in Tohoku more generally. In order to give further backing to this argument we rely on firm surveys reported in earlier research, giving a direct indication, and calculated two measures that indirectly measure how much of the regional economy was affected by the tsunami. Firstly, Todo et al. (2015) and Cole et al. (2015a), based on a survey of firms in the area, indicate that the vast majority of firms was operational within one month, while a small minority was more severely affected up to

[16] We chose to use a dummy of the tsunami, or the height of the wave as our dependent variable rather than the damage incurred or even the level of recovery for two reasons. Firstly, we do not have full information on the damage to all ports. Secondly, both the damage (through the quality of wave defenses) and recovery are potentially endogenous to the local economic situation and port competitiveness.

Figure 3: Tsunami-hit and substitute ports



Note: Data on the height of the wave from the Japanese Ministry of Land, Infrastructure and Transport (2011), the location of the earthquake from the US Geological Survey but this information is not further used in our analysis, exposure from authors' calculations. In the regression analysis Hokkaido ports are not designated as treated.

the point where it could have entirely quit operations.[17] Secondly, we calculated two measures using GIS methods. One measure is based on building structures identified on OpenStreetMaps, and another is based on satellite land cover data.[18] Both measures give similar results, 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% to 0.01% depending on the measure used.[19] These numbers are in line with the survey evidence of Todo et al. (2015) and Cole et al. (2015a). We note that sector or country wide consequences can be controlled for in our empirical specification.

Nevertheless, it is plausible that there was some production changes following the earthquake and important to understand how this could affect our estimates. Therefore,

[17]Both papers use the same underlying dataset of firms in the "Special Great East Japan Earthquake Reconstruction Areas", an area within the Tohohu 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. (2015a) 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).

[18] See Appendix B.2 for further details.

[19]Another way that firms may be affected in their production is when they use intermediate inputs that were shipped through the ports that were struck. In that case we would suspect to observe a similar substitution mechanism for imports as we would see for exports. We do not control for this effect explicitly either, but since the effect would run through the same mechanism, it does not invalidate our setup.

we will revisit this aspect when we incorporate industrial production in our estimations.

3.1.3 A measure for the heterogeneous shock size.

We can control for some variation in the shock to the tsunami-hit and the substitute ports. For the hit ports we have the recorded height of the wave that reached the individual ports, while 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 exposure,

$$\text{exposure}_k = \sum_l \frac{\text{I}(\text{hit}_l) \times \text{wave}_l}{\text{dist}_{k,l}}.$$

So for every port k not hit by a tsunami we measure the distance to all ports l that were hit by the tsunami. Road distances between ports were obtained from an route project based on OpenStreetMaps.[20] We assume that the effect diminishes with distance. Here we expect that the height of the weight is a measure of the destruction that took place and therefore increased the costs of exporting through such a port. In relation to the theoretical model, the wave height will capture the heterogeneous size of the shock to the ports. The distance is measured as the distance between two ports. In the theoretical model what matters really is the distance from ports to a firm. So our measure can only serve as an approximation to the underlying mechanism. Using these measures we can augment model (12) to obtain

$$\begin{aligned} y_{k,g,t} = & \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{hit},\tau} \cdot \text{I}(\tau) \cdot \text{I}(\text{hit}_{k,}) \times \text{wave}_k + \\ & \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{\text{sub},\tau} \cdot \text{I}(\tau) \cdot \text{I}(\text{sub}_k) \times \text{exposure}_{k,g} + \theta_{k,g} + \alpha_{g,t} + \epsilon_{k,g,t}. \end{aligned} \tag{13}$$

We can test the relevance of adding these interactions by inspecting whether the exposure measure improves the inference of the coefficients relative to model (12).

3.2 Data

Based on the customs level export data, we calculate export value (by sector and port) and the empirical margins of trade following Hummels and Klenow (2005). Using k for each (Japanese) port with reference port J representing the sum of all Japanese ports, h for sector, m for destination, I for the product set with individual product code i, and x

[20]See http://router.project-osrm.org

for the export value, the margins are defined as,

$$\text{extensive margin: } EM_{k,h,m} = \frac{\sum_{i \in I_{k,h,m}} \sum_{k \in J} x_{k,m,i}}{\sum_{k \in J} \sum_{i \in I_{k,h,m}} x_{k,m,i}} \times 100,$$

$$\text{trade share: } TS_{k,h,m} = \frac{\sum_{i \in I_{h,m}} x_{k,m,i}}{\sum_{k \in J} \sum_{i \in I_{k,h,m}} x_{k,m,i}} \times 100,$$

$$\text{intensive margin: } IM_{k,h,m} = TS_{k,h,m}/EM_{k,h,m} = \frac{\sum_{i \in I_{h,m}} x_{k,m,i}}{\sum_{i \in I_{k,h,m}} \sum_{k \in J} x_{k,m,i}} \times 100.$$

The margins are calculated for each period independently. The empirical intensive margin as defined here is the sum of the intensive margin and compositional margin from the theoretical model. Destination m 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. Our main analysis will be with a single destination (the world) over a set of 19 sectors, which are defined in Appendix B.5.

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 ¥100M (≈ US\$1M) of exports in 2010. Furthermore, all ports will have margins for all sectors in which they exported somewhere during the sample. So sector 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.[21] 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.

3.2.1 Descriptive statistics

Table 2 presents some descriptive statistics for the variables of interest over the three groups of ports, but without distinction of sectors for brevity. The full period includes the entire sample period from January 2009 to December 2012. The pre- and post-periods present the data for November 2010–Feb 2011, and Mar 2011–June 2011 respectively, with the last column presenting a simple t-test on the means. As is evident from the extensive margin, trade share and number of varieties, the tsunami-hit ports are considerably smaller than the national average, while the substitute, given that these include the ports around Tokyo, are considerably larger than the average. The t-test indicates a statistically significant drop in the the extensive margin, trade share and log of export value of

[21] For the log of export values this creates a minor problem because the log of zero will create missing observations.

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

Statistics, averaged over sectors, for extensive margin (EM), intensive margin (IM), log export value (lValue) and trade share (TS), calculated as defined in the text. 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 counter-factual 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 four month pre-tsunami and post-tsunami period. The final column present the p-value of a simple t-test on the differences between the two periods for each statistic.

tsunami-hit ports, but not in the intensive margin. However, the test does not show a statistically significant for the substitute ports.[22]

3.3 Results

The regression models (12) and (13) estimate the difference of the two types of treated ports *relative to the counterfactual*, while controlling for sector and time fixed effects. Before presenting these results we first show the graphically the time pattern of the average for each type. This is useful to discern whether the counterfactual ports were actually affected in any way by the Great Japanese Earthquake and check for pre-existing trends. Figure 4 present these plots for each of the four trade measures. All measures are demeaned with the means at the port-sector level, in panel (a) we used the full sample to estimate these means, for panel (b) we only use the sample from before March 2011. The dots represent the average value for each month by port type. The smooth-line represents

[22]Density and distribution plots for the ports are presented in Appendix B.1. These plots are informative for the inspection that the tsunami-hit ports and substitution ports, although quite different in their characteristics, are not extraordinary relative to the entire collection of ports of Japan.

a polynomial fit based on all (demeaned) observations for a port type in a period. In other words, this line is estimated separately for each type and for two periods, before and from March 2011. The shaded bands represent 95% confidence intervals.

In these plots the different patterns between the groups pre- and post-tsunami are clearly visible. In both panels, the effect of the tsunami is visible for the ports hit by the tsunami and the substitution ports for all measures except the intensive margin. As a first result this seems to be in line with our theoretical predictions. Specifically for the extensive margin and the log of total exports we find that the tsunami hit port significantly under perform after the tsunami, and the substitution port obtain higher values after the tsunami relative to the counterfactuals. For the log of exports and the extensive margin the pre-tsunami period shows a strong upward trend that appears to flatten by the end of 2010. This pattern is consistent with the recovery of the global trade collapse following the great financial crisis (see for instance Baldwin, 2009; Alessandria et al., 2013).

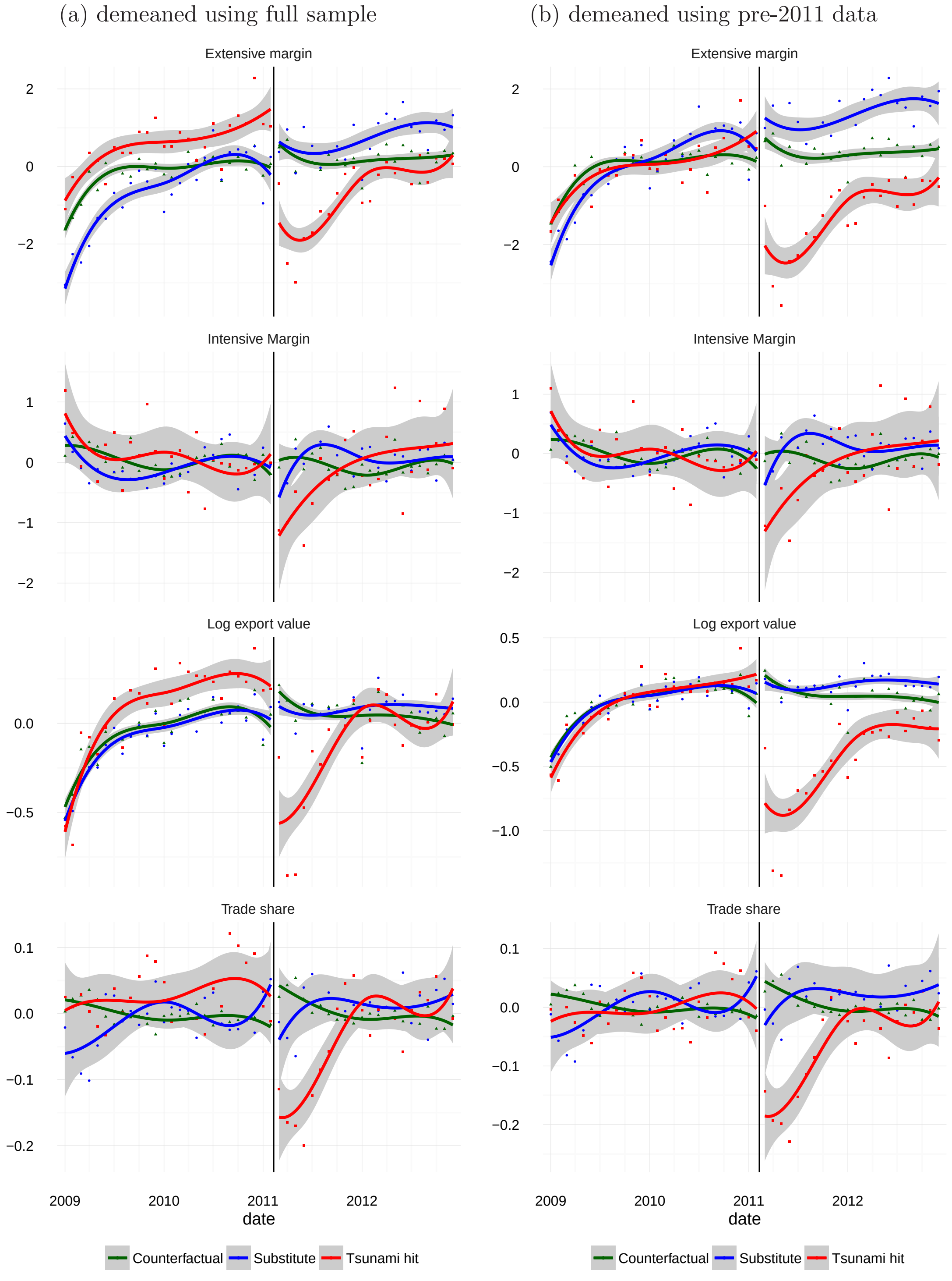
The two types of demeaning presented between the two panels of the Figure are also relevant for the consideration the interpretation of the regressions later. In general the overlap between the three port groups pre-earthquake is better (showing no significant difference) for panel (b). In panel (a) the calculation of port-sector fixed effects uses the entire sample period, including post-earthquake months. Since there is a persistent effect of the tsunami for the treated ports and the pre-tsunami period relatively short, part of the response of the tsunami will be captured by the fixed effects. We can see this in the first panels. Especially the tsunami hit ports appear to be outperforming the other two ports before March 2011. This is an artifact of the differencing procedure. For the substitution ports this effect is causing an under-estimation of the substitution effect, which can be seen by comparing the two panels, especially for the extensive margin and the log of total exports. In the estimation results presented below we will use the standard fixed effect estimation, noting that this underestimates the effect for both the tsunami hit and substitution ports.

Additionally, we can see that counterfactual ports do not indicate a clear change of pattern between the two periods. Nevertheless, for the extensive margin and the log export value there appears an immediate positive effect for the counterfactuals, which is not apparent for the substitution ports. This pattern could potentially limit our ability to estimate a clear substitution effect for the first few months after the tsunami. For the trade share variable we see a declining pattern over time for the counterfactuals before and after the tsunami, but a shift upwards following the earthquake.

Pre-existing trends are hard to spot in the data due to its time-limitation.[23] However, we also find it implausible that exactly those ports that function as substitute following the earthquake would be on a pre-existing trend that make them outperform the other

[23] Additional data would not necessarily be helpful as the cyclical nature of trade will make it hard to distinguish differences in long term trends for the port-groups.

Figure 4: Average trade measures by port-group and time



The dots represent the average of the trade measures after demeaning at the port-sector level. The smoothed 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 extensive and intensive margins and trade share. The log export value the interpretation should use the following adjustment, $\exp(scale) - 1$. Standard errors are not clustered in this representation.

ports.[24]

In summary, we find some underlying patterns for the counter-factual ports, but these are minor relative to the variation observed in the other two types, and if anything indicate that some of the substitution might have been occurring in the counterfactual ports too. Together with a fixed effects approach we are likely to produce conservative estimates of the substitution effect in the regression analysis.

3.3.1 The effect of the tsunami on port-sector margins of trade

The estimation of regressions (12) and (13) 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. The 95% confidence bands are based on clustered standard errors at the regional level.

Figure 5 presents the first results based on model (12). 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 at the last day of the month, the first month in which the data should show an effect from the tsunami would be March 2011. In contrast to Figure 4, these results aim to indicate the difference between the two types of treated ports relative the the counterfactuals. The horizontal zero-axis is accentuated to aid on the inspection of this difference. In this way the plots allow for a range of comparisons, notably, at every point in time while controlling for all fixed effects,

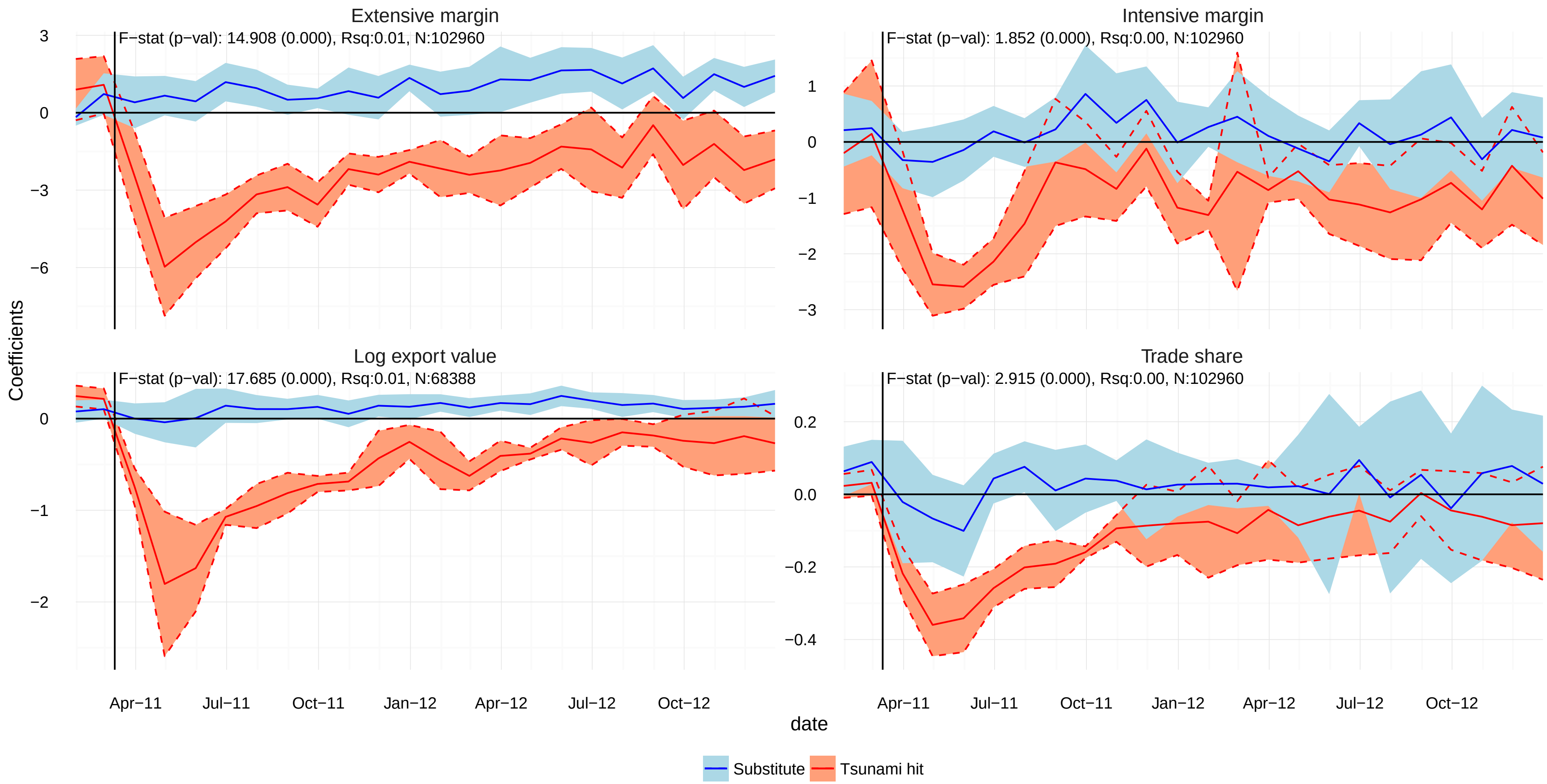
1. for each type (tsunami-hit ports and substitutes) relative to the counterfactual,
2. relative to the two months before the tsunami, and
3. relative to each other.

Each plot represents one regression and some additional statistics of the estimation are indicated. The F-statistic is calculated as the difference between the estimated model and the projected model with no additional regressors.

While one may 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 counter-factual 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 extensive margin and the log of export value indicate the largest,

[24]For instance, one may argue that it is the Tokyo-Yokohama area that continues to attract business and export activity at the cost of the rest of the country. Estimations for each region separately indicate that regions other than the Kanto area have contributed to the substitution effect, see Appendix B.4.1.

Figure 5: The effect of the tsunami relative to counter-factuals, model (12)



Each of the four plots presents the coefficients of a regression of the corresponding trade margins on time dummies interacted with an indicator variable for tsunami hit and substitute ports. The shaded area represents the 95% confidence interval using a clustered covariance matrix (clustered at the regional 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.

statistically most significant and most persistent effects. While the intensive margin and trade share appear to recover within a few months, but indicate overall smaller absolute impacts.

Focusing on the substitute ports we note that the response is much less dramatic relative to the fall of the tsunami-hit ports. This is not surprising overall. As was evident from the descriptive statistics, and indeed our simulations, there are more substitute ports and each of these are on average larger relative to the tsunami hit ports. If there is any trade substitution the effect will be smaller than the shock from the damaged ports. Moreover, any substitution effect will be diminished by the potential that firms reduced output following the earthquake. Still, we find that the extensive margin receives a significant boost at the same time as the the tsunami-hit ports start to return to pre-tsunami levels from the summer of 2011 onward. For the intensive margin 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 of 2012 onward. Finally for the trade share we also find no statically significant effect.

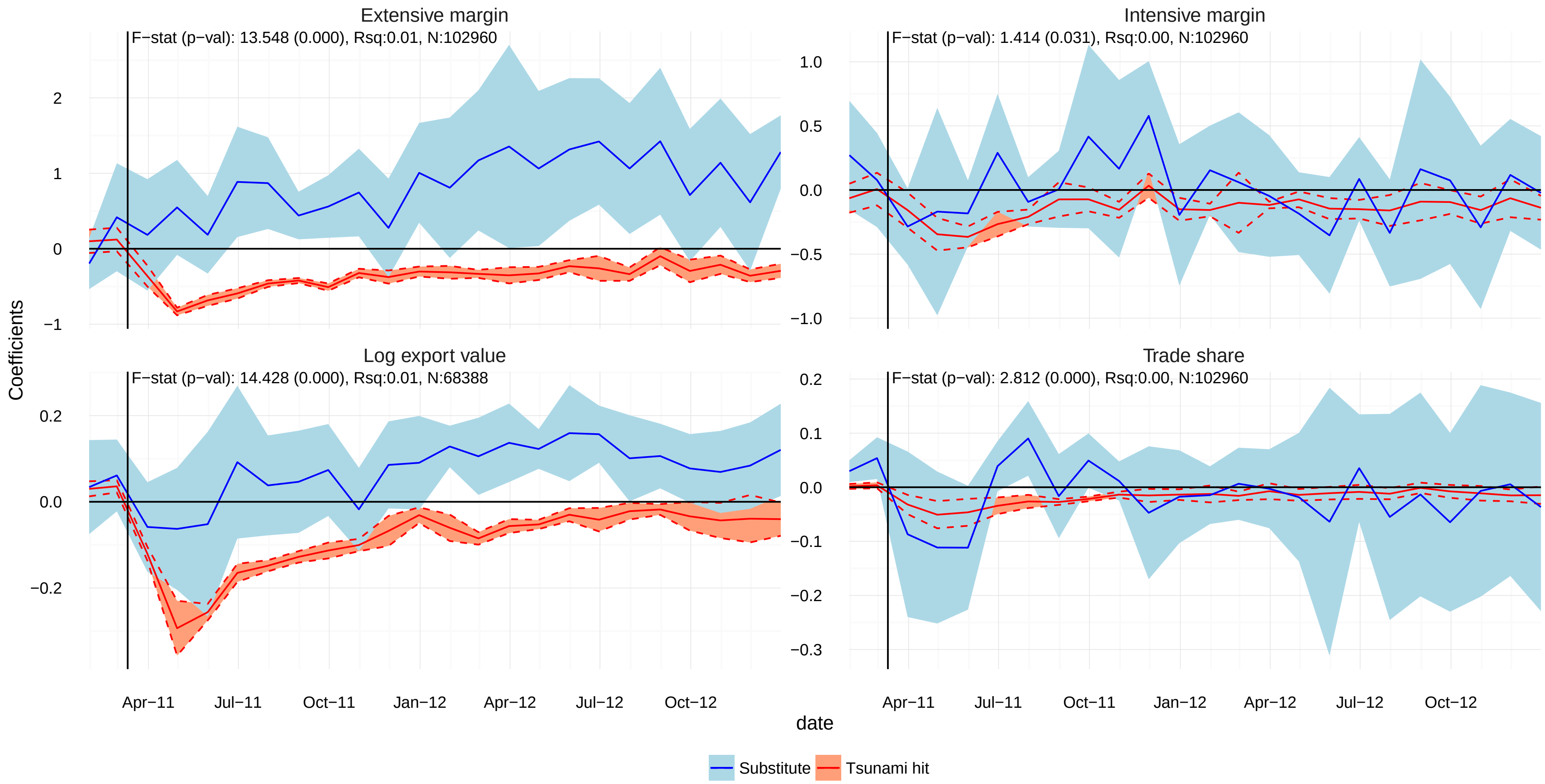
The size of the effects can be read directly from the vertical axes. We can see for the extensive margin that the negative shock for the tsunami-hit ports were around 6 percentage points decline while there is a 2 percentage points increase for the substitutes at their respective peaks. Given the average extensive margin of 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, with values so large these basically indicate a complete stop on exports for the first 2-3 months, which is otherwise not surprising. What is interesting is the relatively quick recovery, while the substitute ports on average at their peaks in May 2012 would have gained around 28.1% ($= (e^{0.248} - 1) \times 100$) in additional exports. The combination of the descriptive statistics with summarised regression statistics explained in Section 3.3.2 below, while taking these estimates as representative and credible, allows us to 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 March 2011 to February 2012, about 40% of exports was substituted to other ports.[25]

From this first set of results we can gain further insights by varying our analysis in

[25]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,

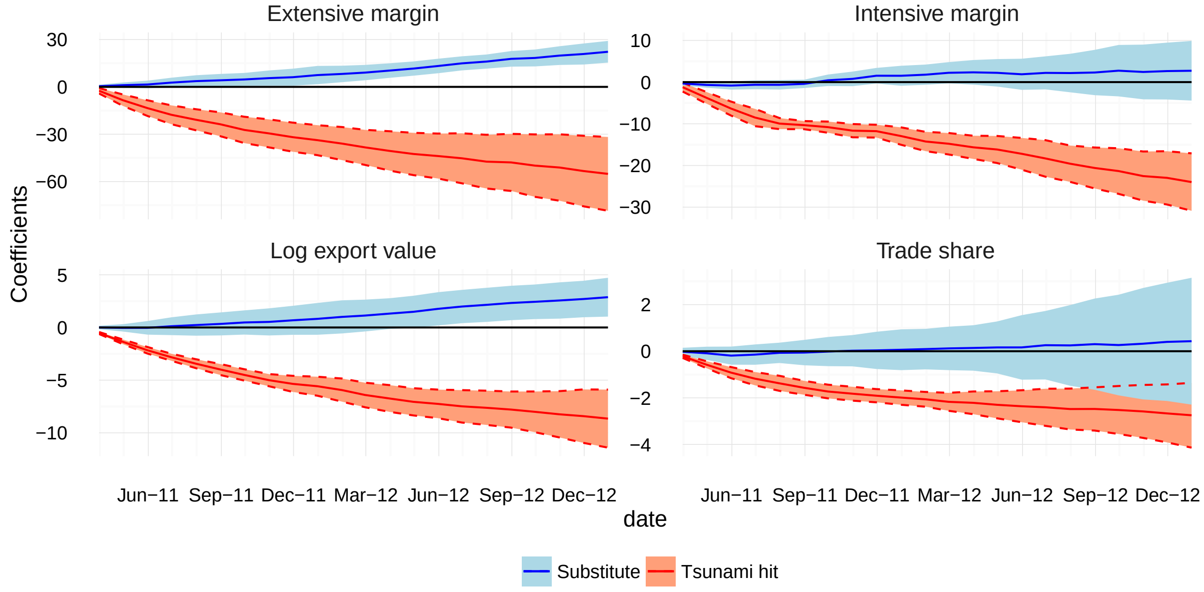
$$(1.132 \times \exp(12.09))/(6.408 \times \exp(11.27)) = 0.401$$

Figure 6: Overall margins of trade, model (13)



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 7: Cumulative effects



Each of the four plots presents cumulative effects of results are presented in Figure 5. The shaded area represent the 95% confidence intervals calculated using the delta method.

various directions. Firstly we will show model (13) using the same margins. Results are presented in Figure 6. There are two major differences, 1) the interpretation for the coefficients now takes into account the unit of measurement, which is in meters of the wave height for the tsunami-hit ports and exposure in terms of wave height meters/distance in km $\times$ 10 (using tens of kilometers scales the measures to comparable amplitudes), 2) the confidence interval for the tsunami-hit ports are much tighter (especially for the extensive margin), but for the substitute ports the precision of the estimates appears not affected as much. As before we find the most significant effects for the extensive margin and the log export value, while the intensive margin and trade share show no statistically significant result.

3.3.2 Cumulative effects

Figure 7 presents a similar graph as above, but the coefficients from March 2011 are presented cumulatively, and the corresponding standard errors are calculated using the delta method. The graph can be interpreted as indicated the cumulative loss or gain over the period. These graphs make it even more clear that the main export substitution effect goes through the extensive margin. This effect also indicates the persistence of the shock, with very little flattening of the curves, or indeed reversal, over time. Moreover, whereas we see that the standard errors increase progressively with time for the intensive margin and trade share, we do not see this to be case for the other two measures.

This cumulative measure also allows us to derive an informative summary measure

Table 3: Summary robustness results

Model		Stat	EM	IM	lValue	TS
Benchmark model (12)	hit	$\sum\beta$	−38.342	−14.786	−6.408	−2.171
		cse	5.669***	1.313***	0.595***	0.197***
		rse	2.147***	2.601***	0.254***	0.198***
	sub	$\sum\beta$	9.043	2.235	1.132	0.121
		cse	2.481***	1.304*	0.771	0.476
		rse	1.390***	1.463	0.231***	0.203
+ cluster at port instead of region	hit	cse	14.180***	5.709***	1.449***	1.011**
	sub	cse	3.471***	1.948	0.653*	0.639
+ $\alpha_{h,t} \times I(\text{elec. reg.}_k)$	hit	$\sum\beta$	−36.249	−15.639	−6.339	−1.773
		cse	5.365***	3.132***	0.787***	0.447***
	sub	$\sum\beta$	9.705	1.726	1.238	0.266
		cse	2.425***	1.951	0.882	0.389
+ pre-differencing instead of F.E.	hit	$\sum\beta$	−35.860	−15.216	−6.903	−2.034
		cse	5.409***	0.968***	0.819***	0.095***
	sub	$\sum\beta$	12.355	1.585	1.376	0.207
		cse	2.290***	0.658**	0.697**	0.463
Exposure model (13)	hit	$\sum\beta$	−5.508	−2.020	−1.442	−0.309
		rse	0.305***	0.362***	0.090***	0.028***
		cse	0.145***	0.154***	0.070***	0.042***
	sub	$\sum\beta$	76.795	7.462	9.482	−2.095
		rse	12.633***	12.026	3.391***	2.042
		cse	20.336***	10.571	8.033	4.166
+ cluster at port instead of region	hit	cse	2.101***	0.997**	0.612**	0.156**
	sub	cse	40.246*	19.400	8.742	5.193

Statistics are the sum of the first twelve months from March 2011 onwards. Standard errors (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 (12) and Exposure following (13) with variations to the Benchmark and Exposure models as indicated. Clustering is at the regional level unless otherwise indicated. $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *

that we can use to compare various estimation methods; we simply 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 these results. The first few lines give the coefficient with the by-region-clustered standard errors as presented in the figures above for the purpose of providing a benchmark against which to evaluate variations on our main specification.

The cumulative statistics are presented in the rows indicates by $\sum\beta$, with directly underneath the relevant standard errors (s.e.), *cse* for clustered and *rse* for robust s.e. 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 statistical significant substitution effect for the extensive margin and the log of export value, but not for the intensive margin and trade share, in line what the graphical representations already indicated.

The robust s.e. are smaller than the clustered ones, which may be expected. We then present by-port clustered s.e., where the coefficients are naturally identical to those of the benchmark. These s.e. are slightly larger compared to the by-region clustered s.e., but qualitatively do not affect our conclusions.

The third model uses a different set of fixed effects, notably by interacting the industry-time fixed effects, $\alpha_{h,t}$, with port-specific electricity region indicator.[26] We find negligible changes in the summarised regression coefficients and the standard errors indicate that this does not alter our main findings.

The fourth set of results present estimates where we estimate a version of model (12), but the fixed-effects are replaced with left-hand-side variables that are demeaned at the port-sector levels, as presented in the Figure 4 panel (b). The idea again is that the usual fixed effects absorb some of the actual impact of the shock.[27] We find indeed that the estimated point estimate have increased for substitute ports, and that this is in particular relevant for the Extensive margin and the Log of exports value and their standard errors. However, the difference with our benchmark is not very large for these estimations, further supporting the general robustness of our empirical setup.

The last set of results present variations for model (13) with respect to the estimation of the variance-covariance matrix and derived standard errors. Note that the point estimates of coefficients should be interpreted again with the unit of account of the interaction variable, wave height for the tsunami hit ports, wave height/10 km for the substitutes.

[26] As the country is divided in a 50Hz and a 60Hz region, with very limited interconnections, it may be possible that a large electricity disruption will be limited to one region. However, all nuclear plants were shutdown after the breakdown of the Fukushima disaster, so essentially the electricity shock was nation-wide.

[27] Our model can be summarized in a standard panel framework,

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

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 $\bar{y}_i = \frac{1}{26}\sum_{t=\text{Jan 2009}}^{\text{Feb 2011}} y_{i,t}$, which excludes D' 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 $\ddot{y}_{i,t} = y_{i,t} - \bar{y}_i$, and $\epsilon_{i,t}$ is the transformed model error. This procedure relies on the assumption that $\bar{y}_i$ is a consistent estimator of c_i. A fixed effects estimator would follow the same approach, but will use the entire time sample available including the period after March 2011 to estimate c_i. Note that a specific time trend is not included in this case. Alternatively, one 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 the a period longer than one year and we would not want to compare the impact in April in 2012 against April 2011. Instead what we are after is to demean all effects from 2011 onwards 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 counter-factual ports.

3.4 Effects of industrial production

As acknowledged above, our estimates might be biased when the earthquake and tsunami not only affected ports but also firms. Indeed, several papers have specifically studied the effects on firms following this event (Todo et al., 2015; Cole et al., 2015a).

We consider two potential channels. First, a firm located close to its preferred port could have decreased production. Second, the decreased production might have been replaced by another plant or firm at another location, either in the same area or in another part of the country. This second channel includes the potential of multi-plant firms to move production to other areas.

The first channel would cause an over-estimation of the tsunami hit effect, as the decline of exports is not solely due to the port but also to the supplying firms. However, the substitution effect would be *underestimated*, because declining production would diminish the chance of observing increased exports in substitution ports. This could be both for the case where firms with damage would ship less to their preferred unaffected port, or because it served as an supplier of intermediate products to a firm that used an unaffected port.

The second channel, where production is relocated, could potentially increase production in an area close to a substitution port. Note, however, that such plant substitution could also happen to areas of counter-factual ports or ports hit by the tsunami. 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 re-routing 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.

We do not have firm level data at 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 categories of sectors/products categories that we consider. However, prefecture level data of total industrial production at the monthly frequency is available.

Firstly, as control variables $z_{k,g,t}$ in equation (12) we add both the monthly aggregate industrial production for the prefecture in which a port is located, own prod.$\equiv \log(production_{k,t})$, as the cumulative industrial production of the treated or non-treated region (excluding the production of a port's own prefecture), reg. prod. $\equiv \log(\sum_{l=-k} production_{l,t})$.[28] See Table 4 for these results. The coefficients on the two production variables indicate that production is positive correlated to trade, but importantly not statistically significant

[28]Data from the Japanese Ministry of Industry website. To be precise, the 'treated or non-treated' for certain ports is defined based on the treatment area. For ports in Tohoku, Kanto, Hokoriku and Tokai it is the sum of all prefectures in this area, for prefectures outside of those four regions the surrounding prefectures are the sum of all except in those four.

Table 4: Prefecture production as control variable

Model		Stat	EM	IM	lValue	TS
Benchmark	hit	$\sum\beta$	−38.342	−14.786	−6.408	−2.171
		cse	5.669***	1.313***	0.595***	0.197***
	sub	$\sum\beta$	9.043	2.235	1.132	0.121
		cse	2.481***	1.304*	0.771	0.476
Benchmark with production	hit	$\sum\beta$	−25.369	−12.936	−5.143	−1.159
		cse	2.608***	2.414***	0.620***	0.305***
	sub	$\sum\beta$	11.137	3.072	2.005	−0.033
		cse	2.640***	1.605*	0.878**	0.367
	own prod.	β	4.817	0.347	0.904	0.291
		cse	2.908*	1.005	0.657	0.166*
	reg. prod.	β	2.408	−0.513	0.782	0.297
		cse	3.364	1.844	1.128	0.398

Statistics are the sum of the first twelve months from March 2011 onwards. Standard errors (cse for clustered and rse for robust) are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$. Estimated following (12) and $z_{k,g,t} = \{\text{own. prod}_{k,t}, \text{reg. prod}_{k,t}\}$. Clustering is at the regional level. $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *

for log export value, while the cumulative impact is little changed from our benchmark specification.

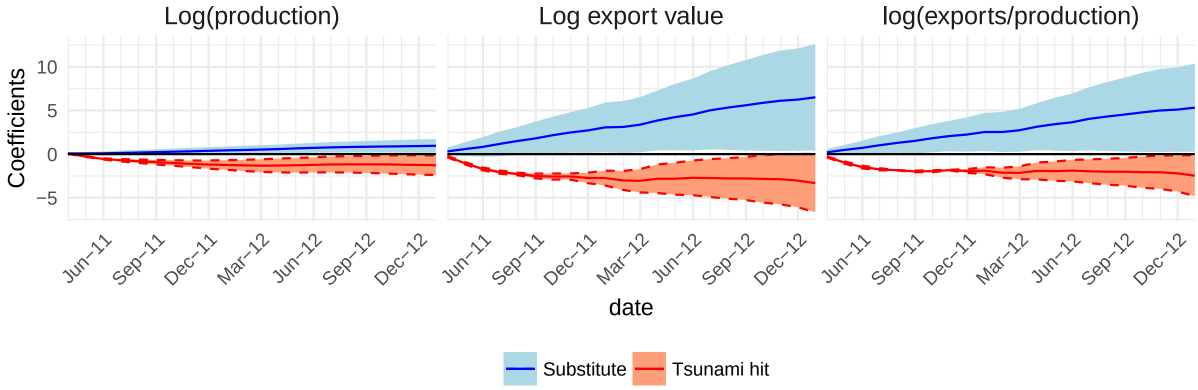
Secondly, we incorporate production directly in the dependent variable. We create a measure of total export at the prefecture level by summing individual ports exports. Then we create the ratio of exports over production to have a production adjusted measure of exports:

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

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. We present graphically the result of the cumulative impact of the disaster on exports and production at the prefecture level for exports and production in Figure 8.[29] The figure 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 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.

[29] Further results are presented in Appendix B.4.3. The loss of detail from a sectoral analysis will affect the precision of the estimates.

Figure 8: Cumulative impact with prefecture production



3.5 Sectoral differentiation

Having estimated an average substitution effect we recognise that there could be a large variety between sectors. Some ports may be more specialised in certain sectors due to the nature of the regional production. At the same time different products may have different possibilities and needs to be substituted. For instance, goods that are part of a supply chain may respond stronger than goods that have less time pressure on delivery and can be stored at the plant for some time.

First, we discuss how our theoretical model can incorporate variations in sectoral responses to changes in fixed and variable costs. Thereafter, we estimate the substitution effect for various sectors and destinations.

3.5.1 Numerical Simulation

The main parameter in our model that can approximate the difference in characteristics for various products between product groups is the size of the elasticity of substitution, σ. In order to understand the effect of σ on the substitution effect we first calibrate our model with benchmark parameters and then offer some simulations.

For the benchmark simulations, 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 standard and in line with the literature. 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.[30]

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

Table 5: Results of a simulationMargins Decomposition

Elasticities	E.M.	I.M.	C.M.	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
$d\ln X/d\ln f_H$	−0.48	0.00	0.51	0.09
$d\ln X_H/d\ln \mu_H$	−11.53	−5.00	5.76	−10.76
$d\ln X_S/d\ln \mu_H$	0.34	0.00	0.83	1.17
$d\ln X/d\ln \mu_H$	−2.72	−2.08	2.88	0.02

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 5 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.[31] First, following a one percentage points 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 ($X_H/X_S = 0.1762$), extensive margins ($EM_H/EM_S = 0.3677$) and intensive margins ($IM_H/IM_S = 0.8211$), there is a smaller adjustment for substitute S port in all types of margins as well as total export. For instance, extensive margins decrease by −2.05 percentage points for tsunami hit H port while those for substitute S port increases by 0.06 percentage points. Second, the adjustment in terms of extensive margins is larger than that in intensive and composition margins for both types of ports. Third, it is striking to notice that there is a *positive* adjustment for aggregate trade flow. Total export *increases* by 0.09 percentage point following f_H shock, respectively. This is due to a substitution effect across ports that we have argued combined with a larger size of substitute port at the steady state. The above mentioned three patterns are similar for internal transportation costs shock, μ_H but with a larger magnitude.

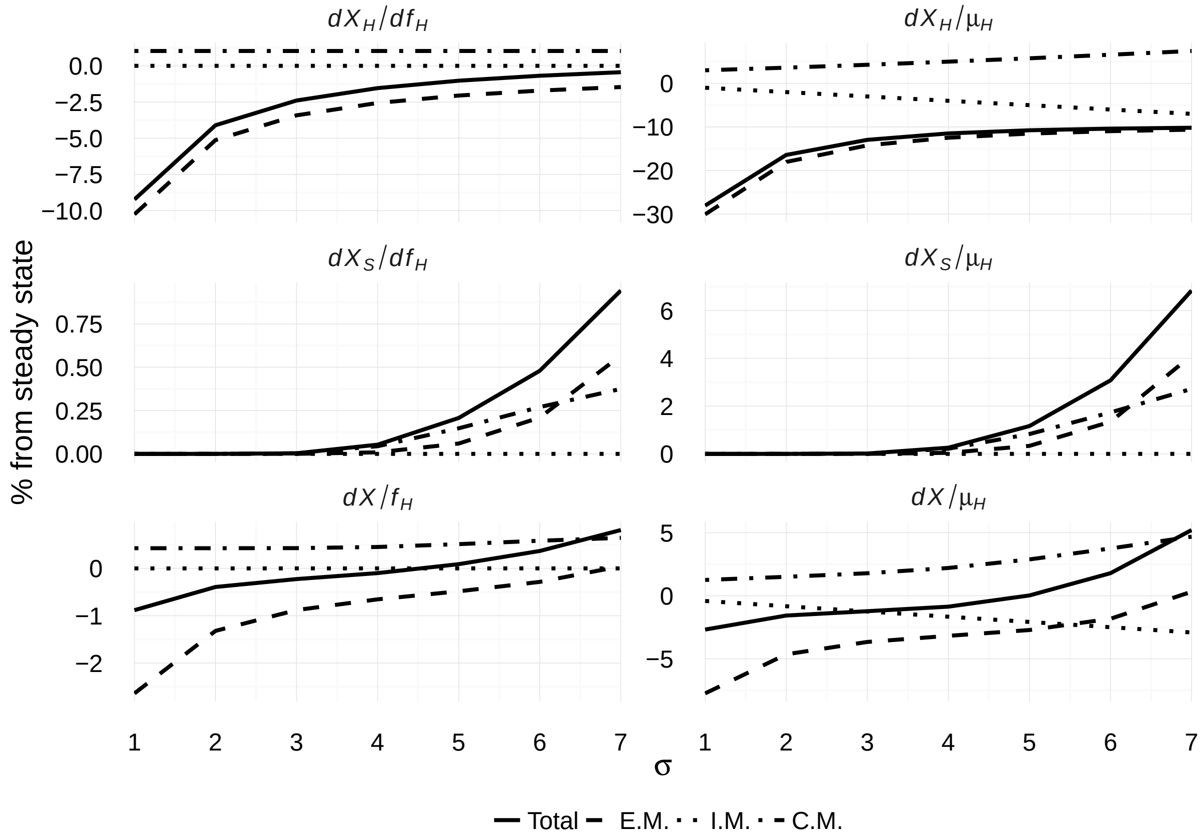
Figure 9 shows the results of the sensitivity analysis against the elasticity of substitution, σ.[32] The first column in the figure shows the results for f_H shock for each tsunami hit and substitute port as well as aggregate flow. For extensive margins, with a lower value of σ, there exists a stronger negative adjustment in tsunami hit H port. On the other hand, a stronger positive adjustment appears with a higher value of σ for substitute S port following the same shock. However, such a non-linearity disappears for intensive and composition margins and the adjustments are insensitive with respect to the value of

state.

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

[32]In computing Figure 9, we fix κ and f_H, f_S, μ_H and μ_S as in Table 5. Restrictions on parameters that allow a multiple port structure as argued in Proposition 1 are satisfied in the figure.

Figure 9: Sensitivity Analysis on σ



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.

σ for both types of ports. The second column in the figure shows the result for μ_H shock where we find a similar result but with a larger magnitude.

3.5.2 Estimating the substitution effect by sectors

We do not observe the elasticity of substitution 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 subscripted by h). Rather than presenting this graphically we calculated again the sum over the 12 month period from March 2011 onward. Table 6 presents results where each row represents a separate regression.[33] The results are ordered descending by the extensive margin. What

[33]Not all sectors are present. We estimate or model where at least nine of the 15 tsunami hit ports had positive exports for each period from March 2011 to December 2012. Plots from individual sectors are available on request. The fixed effects exclude the sector subscripts as well, resulting in time and port fixed effects for each regression.

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 negative effects of the extensive margins 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 again, but for the substitution effect we cannot detect a statistically significant effect for most ports.

Different values of σ for different sectors could provide an explanation for this result as indicated by the simulations. Additionally, as suggested by Todo et al. (2015), the supply chain may be critical especially for the technology goods that are included in the categories of the first to sixth row. 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.[34] Finally, the negative effect of the extensive margin of iron and steel could be further motivated from increased domestic demand for reconstruction purposes.

3.6 Margins of trade by destination

As a final exploration we look at the effects by destination regions (similarly as before, as if our β are subscripted by m for destinations).[35] 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 would give insight into whether destinations are treated differently, 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 7.

The results indicate that the substitution effect is the biggest for the closest markets, Asia, and Middle and South America. Therefore, trade distance and market size seems 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 chain linkages between Japan and Mexico for the North American market. The other regions have both smaller coefficients

[34] Cole et al. (2015a), using a sample of surveyed firms, find that most firms that experienced significant damage are across all sectors, but with specific concentration in a sector called 'Production Machinery'.

[35] 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 6: Differentiated effects over sectors

Sector	stat	EM hit	EM sub	lValue hit	lValue 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

Calculations based on model (12) for each sector separately. Statistics are the sum of the coefficients for the first twelve months from March 2011 onwards. Clustered standard errors are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$.

which are statistically not different from zero at the usual significance levels. For Africa we even find a negative substitution effect, much like we found negative coefficients for some sectors. This would indicate that there might be some further replacement going on, for instance where the counter-factual ports are taking over some of the trade to Africa while the substitute ports concentrate on the main markets.

Table 7: Differentiated effects over destination regions

Sector	stat	EM hit	EM sub	lValue hit	lValue sub
Middle and South America	$\sum\beta$	−31.377**	26.646***	−3.524***	1.448
	cse	13.332	5.228	0.860	1.123
Asia	$\sum\beta$	−30.508***	12.455***	−2.757***	2.382**
	cse	4.310	4.593	0.840	1.196
North America	$\sum\beta$	−12.320	8.279	−4.319***	3.563**
	cse	18.570	16.349	1.234	1.758
Central and East Europe, incl. Russia	$\sum\beta$	−42.343**	6.627	−5.270***	1.018
	cse	17.503	8.532	0.830	1.664
Western Europe	$\sum\beta$	−28.442***	6.417	−2.068**	2.352
	cse	8.549	7.986	0.927	1.634
Oceania	$\sum\beta$	−23.711***	3.852	−4.979***	1.441
	cse	4.096	10.567	1.118	1.029
Middle East	$\sum\beta$	−7.046	3.469	−4.803***	0.724
	cse	18.506	22.091	0.757	0.973
Africa	$\sum\beta$	−53.237***	−8.901	−3.290***	2.997**
	cse	6.475	14.944	1.171	1.279

Calculations based on model (12) for each destination region separately. 'Groups' are defined as country-destinations rather than sectors. A group is than defined as the countries belonging to the geographical region. Statistics are the sum of the coefficients for the first twelve months from March 2011 onwards. Clustered standard errors are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$.

3.7 Robustness

In Appendix B.4 we present further robustness results. First, we estimated the effect for each of the four Japanese treatment regions separately. These results indicate that it is not one region that drives the result but the effect is present for all regions although estimating parameters for each region separately results in a loss of precision. For good measure we estimated the effects for Hokkaido as well.

As was evident from Figure 4 the three groups of ports had very similar trends before the tsunami. We included industry-time fixed effects in the main specification, and allowed for differences based on electricity region in Table 3. Admittedly, all these are not rigorous tests on pre-trends driving our results. Since the data is limited to two years before the disaster we can not exploit a much better estimation on long-term trends. This could be particular problematic if the trade from Tokyo-Yokohama area would develop significantly stronger relative to the rest of the country. We note that Kanto area, which includes Tokyo, indicates the smallest substitution effect among the various regions (See appendix B.4.1) and therefore appears to contribute the least to our estimated substitution effect.

Second, 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 counter factual ports as substitute (while excluding substitute ports from the treated regions). All these function as a test on our selection of substitute ports. None of these results alter the conclusions we can draw from the main results.

Finally, as indicated above, we present additional results on measures of export values relative to prefecture production in Appendix B.4.3. This varies the level of exports at the port-sector, custom and prefecture level, while dividing exports at these levels always with prefecture level industrial production. The results indicate that while production does slightly reduce the size of the substitution effect it does so without loosing statistical significance.

We have also performed all the above analysis on the trade measures computed at the port level, rather than by port-sector, with qualitatively similar results.[36]

4 Conclusion

In this paper, 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 characterised 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 is conditional on the existence of both internal variable and fixed trade costs. We analytically present comparative statistics results for total trade, extensive and intensive margin of trade and show how the switch of exports from one port to the another can be accounted for by exogenous variation in either changes in the transportation costs from firm to port and port specific fixed export costs. We test the prediction of the model with Japanese customs data and find a supportive evidence for a port substitution following the 2011 Great Japanese Earthquake. We find a significant and economically meaningful substitution effect. Back-of-the-envelope calculations suggest that about 40% of exports was substituted to other ports. We also find substantial differences across product categories and destinations.

The findings in this paper have implications for policy makers. Firstly, disaster preparation is an issue across the world with devastating storms and earthquake striking regularly. The ability of economies to recover from such events has been related to the ability of firms to have alternative options and routes to ship their goods. Secondly, policy makers interested in stimulating exports might want to take into account how changes in port specific facilities would affect neighbouring regions.

[36]Results available on request and also in an earlier working paper (Hamano and Vermeulen, 2017).

The implication of this article is that internal barriers to trade are to a large extent mitigated by the ability of firms to choose among a number of route options to bring their products to international markets, which helps during unexpected events such as the one we exploited in this paper. The substitution effect is most evident for product varieties that we know to play a big role 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. Reversing the argument, we expect that infrastructure investments for new or existing ports could potentially facilitate new trade for product that were previously too costly to transport internally, while product categories that are part of an international supply chain might switch between ports but would not affect aggregate export volumes to a large extent.

Inevitably we left some dimensions unexplored. We took firms' locations with respect to ports as given, which was appropriate for the empirical setup. However, both the location of firms and the number of ports might be endogenous when we consider infrastructure policy. As our empirical results indicate that the initial shock of the natural disaster has a diminishing impact over time for some ports and sectors, one could imagine that firms are forward looking and anticipate such adjustments, and thereby introduce a dynamic aspect to decision of firms to trade. However, at the same time our data indicates a persistent effect on substitution ports, in line with evidence from other cases. From this paper it remains unclear what could drive firms to permanently switch export route even if ports are completely reconstructed.

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A Theoretical Appendix

A.1 Proof of Proposition 1

First we look the ranking condition of cutoff productivity levels. From (4) and taking the ratio of ZCP of two ports k and s with $k > s$,

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

We have $\overline{\varphi}_{ijk} < \overline{\varphi}_{ijs}$ when $f_{ijs}/f_{ijk} > (\mu_{ijs}/\mu_{ijk})^{1-\sigma}$. Also dividing (6) by profits for port s,

$$\left(\frac{\overline{\varphi}_{ijks}}{\overline{\varphi}_{ijs}}\right)^{\sigma-1} = \frac{\mu_s^{-(\sigma-1)}}{\mu_s^{-(\sigma-1)} - \mu_k^{-(\sigma-1)}} \left(\frac{f_{ijs} - f_{ijk}}{f_{ijs}}\right) = \frac{1 - \frac{f_{ijk}}{f_{ijs}}}{1 - \left(\frac{\mu_k}{\mu_s}\right)^{1-\sigma}}$$

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

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

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

From (3) and (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 s. Deriving these expressions with respect to $\varphi^{\sigma-1}$ for each port, we have $(\mu_k/\mu_s)^{\sigma-1} > 1$ so that (A-1) holds. On the other hand, when $(\mu_k/\mu_s)^{\sigma-1} < 1$, 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 (5), 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.

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

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

A.2 Further Comparative Statics

Here we present additional comparative statics results in addition to those presented in the main text. Specifically, the comparative statics on on internationl trade costs, τ, quality-demand shifter, q and national labour productivity Z indicate that the mulitple port structure does not affect the response of exports to external changes. shocks that are independent of port characteristics, namely τ, Z_i and q, have exactly the same impact on 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, extensive margins decrease with the elasticity of $-\kappa$ while average export remains unchanged because of reduced intensive margins 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.[37]

The comparative statics on changes in the fixed and variable costs on port S indicate shocks on the S port, instead of the H port give the same qualitative effects of substition. So if we were to switch the two ports in their comparative advantage structure we will find the same signs of the effects, but the magnitudes will be different. The reason is that the firms that allocate to the two ports are different, so any change in the ports fixed or variable costs, affects a different set of firms, giving rise different magnitudes in the effect of exports.

[37] The same expression is provided by Chaney (2008) with a single port case.

Table A-1: Additional comparative statics

(a) Margins Decomposition

Elasticities	E.M.	I.M.	C.M.	Total
$\mathrm{d}\ln X_H/\mathrm{d}\ln\tau$	$-\kappa$	$-(\sigma-1)$	$\sigma-1$	$-\kappa$
$\mathrm{d}\ln X_H/\mathrm{d}\ln q$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$\mathrm{d}\ln X_H/\mathrm{d}\ln Z$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$\mathrm{d}\ln X_H/\mathrm{d}\ln f_H$	$-\frac{\kappa}{\sigma-1}\mathsf{F}_H$	0	F_H	$-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_H$
$\mathrm{d}\ln X_H/\mathrm{d}\ln f_S$	$\frac{\kappa}{\sigma-1}\mathsf{F}_S$	0	$-\mathsf{F}_S$	$\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_S$
$\mathrm{d}\ln X_H/\mathrm{d}\ln\mu_H$	$-\kappa\mathsf{U}_H$	$-(\sigma-1)$	$(\sigma-1)\mathsf{U}_H$	$-[\kappa-(\sigma-1)]\,\mathsf{U}_H-(\sigma-1)$
$\mathrm{d}\ln X_H/\mathrm{d}\ln\mu_S$	$\kappa\mathsf{U}_S$	0	$-(\sigma-1)\mathsf{U}_S$	$[\kappa-(\sigma-1)]\,\mathsf{U}_S$
$\mathrm{d}\ln X_S/\mathrm{d}\ln\tau$	$-\kappa$	$-(\sigma-1)$	$\sigma-1$	$-\kappa$
$\mathrm{d}\ln X_S/\mathrm{d}\ln q$	κ	$\sigma-1$	$-(\sigma-1)$	κ
$\mathrm{d}\ln X_S/\mathrm{d}\ln f_S$	$-\frac{\kappa}{\sigma-1}\Gamma_S$	0	$-\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_S+\frac{\kappa}{\sigma-1}\Gamma_S<0$	$-\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_S$
$\mathrm{d}\ln X_S/\mathrm{d}\ln f_H$	$\frac{\kappa}{\sigma-1}\Gamma_H$	0	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H-\frac{\kappa}{\sigma-1}\Gamma_H>0$	$\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_H$
$\mathrm{d}\ln X_S/\mathrm{d}\ln\mu_S$	$-\kappa\Theta_S$	$-(\sigma-1)$	$-[\kappa-(\sigma-1)]\,\Lambda_S+\kappa\Theta_S<0$	$-[\kappa-(\sigma-1)]\,\Lambda_S-(\sigma-1)$
$\mathrm{d}\ln X_S/\mathrm{d}\ln\mu_H$	$\kappa\Theta_H$	0	$[\kappa-(\sigma-1)]\,\Lambda_H-\kappa\Theta_H>0$	$[\kappa-(\sigma-1)]\,\Lambda_H$

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 Extensive margin (E.M.), Intensive margin (I.M.) and Composition margin (C.M.)

(b) Parameters

$\overline{f}_H>0,\ \overline{f}_S>0,\ \overline{\mu}_H>0,\ \overline{\mu}_S>0$	$\overline{f}_H/\overline{f}_S>(\overline{\mu}_H/\overline{\mu}_S)^{\sigma-1}>1$
$\mathsf{F}_H=\frac{1}{1-\frac{\overline{f}_S}{\overline{f}_H}}>1$	$\mathsf{F}_S=\frac{1}{\frac{\overline{f}_H}{\overline{f}_S}-1}>0$
$\mathsf{F}_H>\mathsf{U}_H=\frac{1}{1-\left(\frac{\overline{\mu}_H}{\overline{\mu}_S}\right)^{\sigma-1}}>1$	$\mathsf{U}_S=\frac{1}{\left(\frac{\overline{\mu}_S}{\overline{\mu}_H}\right)^{\sigma-1}-1}>\mathsf{F}_S>0$
$\Gamma_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\mathsf{U}_S}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\mathsf{F}_S}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>1$	$\Delta_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\mathsf{U}_S}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\mathsf{F}_S}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>1$
$\Theta_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\mathsf{U}_S}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\mathsf{U}_S}{\left[\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1\right]}>1$	$\Lambda_S=\frac{1}{1-\left(\frac{\mathsf{F}_S}{\mathsf{U}_S}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\mathsf{U}_S}{\left[\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1\right]}>1$
$\Gamma_S>\Gamma_H=\frac{\mathsf{F}_H}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>0$	$\Delta_S>\Delta_H=\frac{\mathsf{F}_H}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$
$\Theta_S>\Theta_H=\frac{\mathsf{U}_H}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}}-1}>0$	$\Lambda_S>\Lambda_H=\frac{\mathsf{U}_H}{\left(\frac{\mathsf{U}_S}{\mathsf{F}_S}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$

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

B Empirical Appendix

B.1 Additional statistics on ports

Figure B-1: Density plot - port level

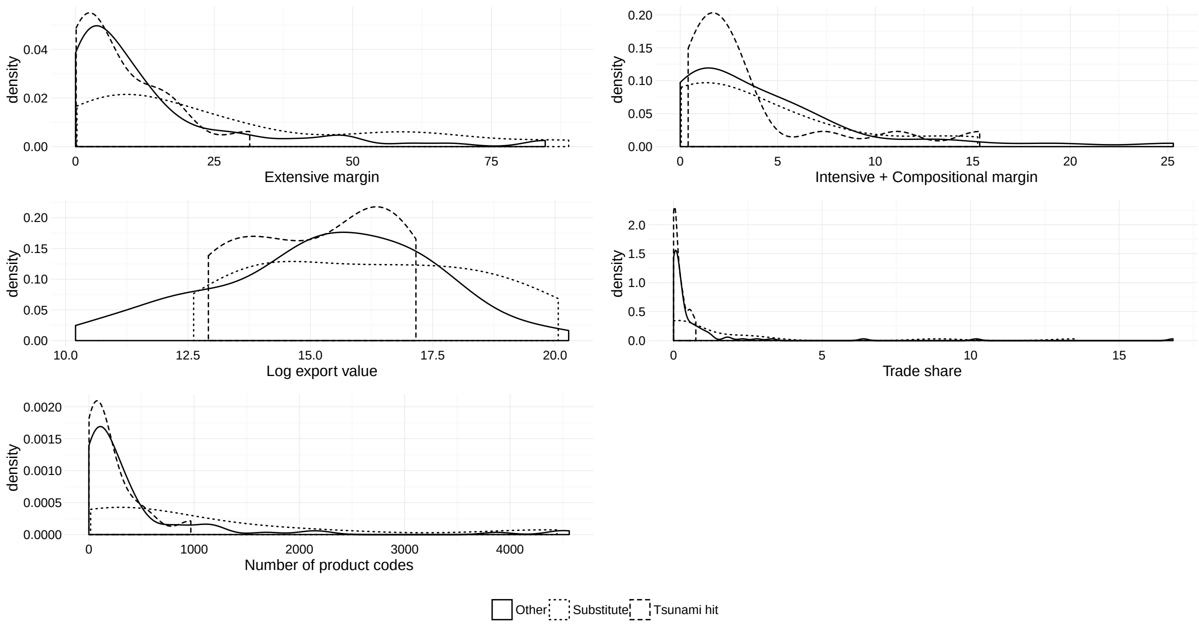


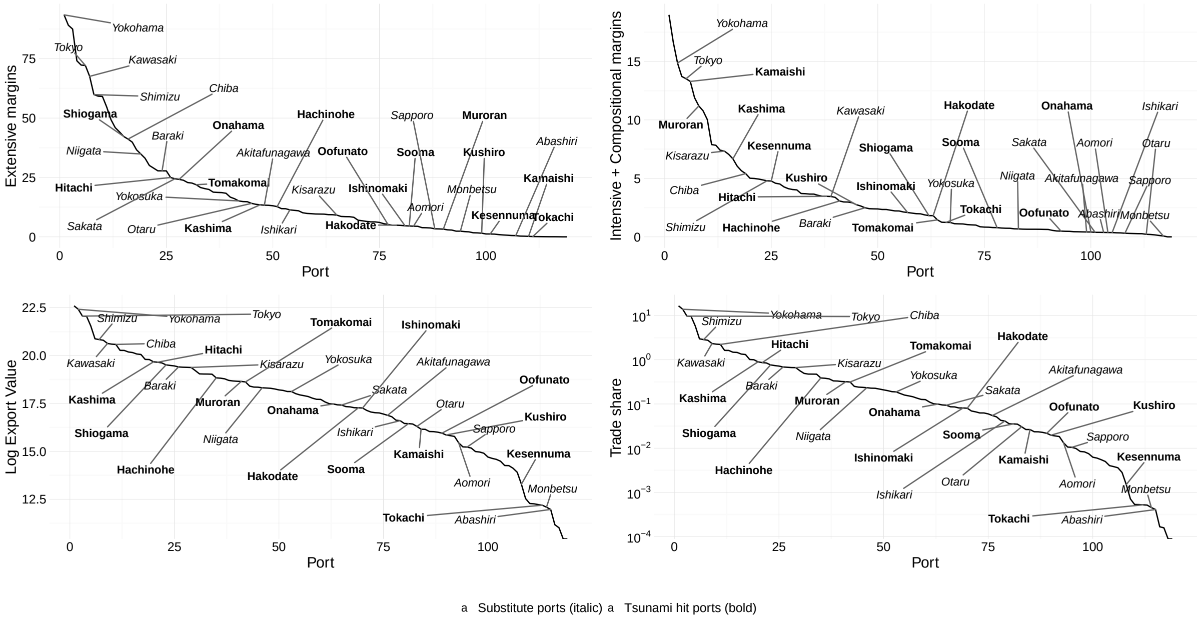
Figure B-1 gives a representation of the distributions of the four key variables, grouped as tsunami hit ports, substitutes and other. The plots are based calculated using the average margins or values over 2009-2010 (i.e. pre-tsunami), without sector definitions. The density plots are calculated for 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 intensive margin. The substitute ports are skewed towards the low end of the trade margins, but in terms of export value appear centered relative to the other ports.

B.2 Direct flood impact

In order to substantiate that the tsunami primarily hit ports in the Tohuku and Kanto region, but not the wider economy around it we provide statistics on the affected region using two different datasets. Figure B-3 gives an overview of the two underlying data of the approaches, zoomed in around the Sendai port area, one of the worst hit areas.

We obtained a shape files of the flooded region from Geospatial Information Authority of Japan (GSI Japan, part of the Ministry of Land, Infrastructure, Tourism and Transport), which contains a number of polygons that indicate the maximum flood extend. These were created using arial images during the crisis and continuously updated as new

Figure B-2: Ports ranked by trade measures (2010)

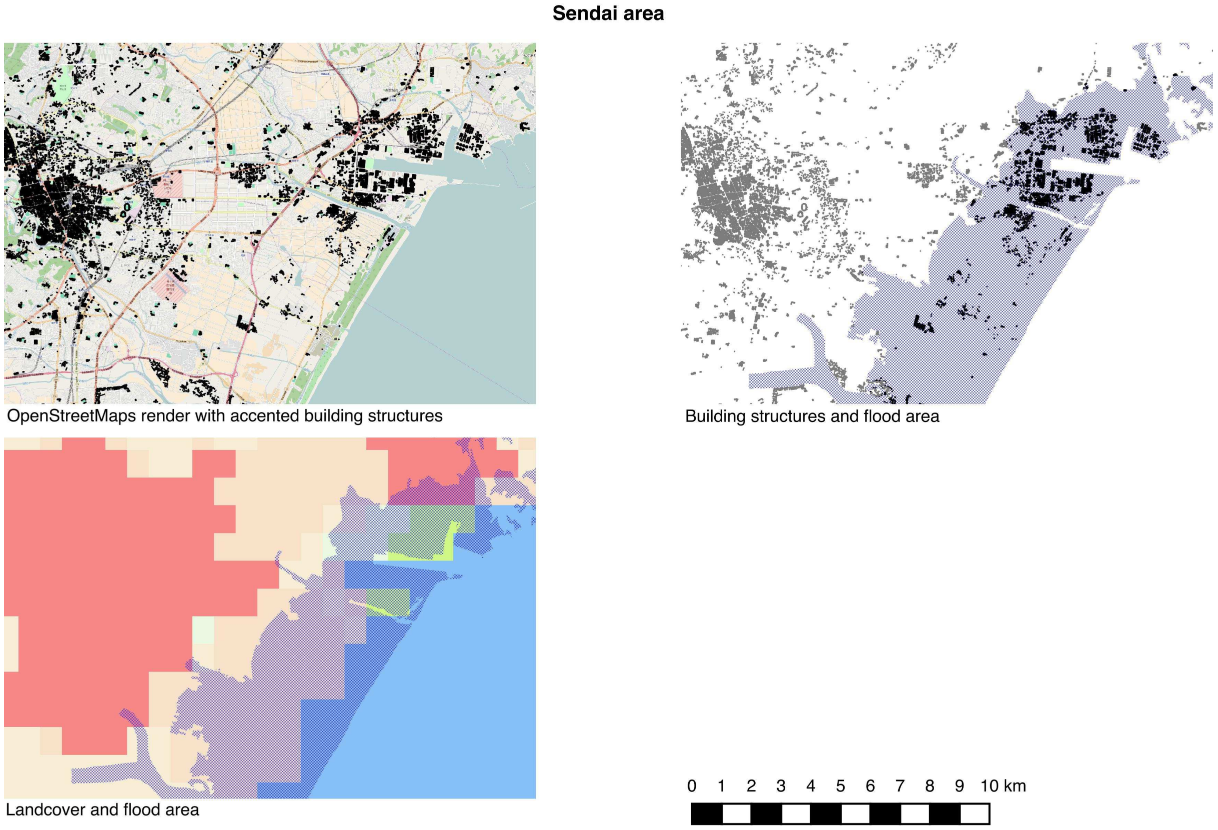


information came on the actual reach of the water (Nakajima and Koarai, 2011). We spatially interacted these polygons with two data sources.

Firstly, 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 OpenStreetMaps (OSM) data is 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 data set. 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.

Secondly, we used a raster file on landcover from the GSI Japan. We took the raster data of 2006 (Global Map Japan version 1.1 Raster data). Only one value of the raster band relates to build-up area. Panel 3 showcases this data, build-up are is light-red and concentrated around the city centre and north of the port area. In this case the data does not appear very accurate in placing the industrial area around the port. On the other hand, the area north of the port is considered build-up whereas relatively few structures are identified at that place in the OSM data. Each cell in the raster presents a certain area. 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. This should give us a conservative figure. We find that 0.01% in Kanto and 4.67% in Tohoku of build-up area was affected by the floods.

Figure B-3: Measures of direct physical impact of the tsunami



In conclusion, neither of the two datasets is perfect for giving a measure of the number of business directly affected by the Tsunami. For the Tohoku region the two measures give a rather similar figure of around 5% of industrial and commercial land being affected, while the relevant number for the Kanto region is much lower.

B.3 Port damage and port specialisation

We establish in this section two features in the data. Firstly, the damage done to ports was heterogenous. Secondly, different ports have different specialisations. 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 heterogenous effects on ports . A summary of this work is presented in Table B-2. The table indicates the number of berths for 11 ports that were hit by the tsunami, initially, the number still functional right after, and those available after 520 days (about 17 months). The data indicates the variation in size, heterogeneity in destruction and difference in recovery. The number of berths in function 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

Table B-2

Port	Prefecture	Wave height	Number of operating Berches initial	t=0	t=520
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	23	44
Shiogama	Miyagi	6.0	42	11	40
Onahama	Fukushima	3.3	72	4	8

Table B-3

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

prefer not to use this periods as damage to 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 to 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. Taking into account actual damage will be problematic as it will include potentially endogenous factors.

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 B-3 indicates that different ports have different specializations.

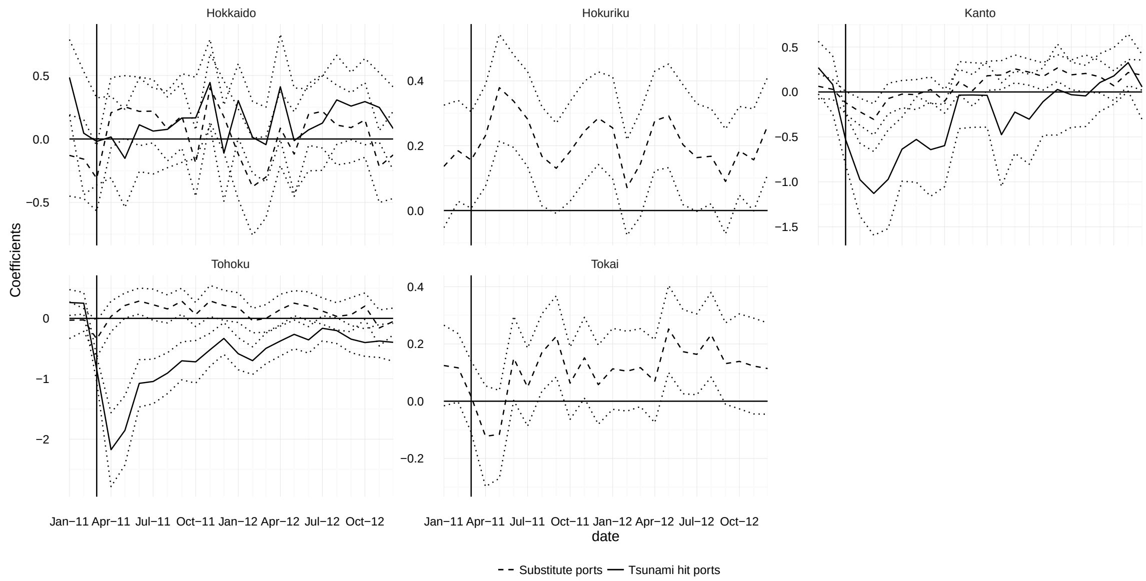
The combination of the two Table functions to show the heterogeneity between ports, not only in size as indicated in Figure B-1 and B-2 but also by sectors that require different types of facilities. The damage done to ports was also heterogenous, as was the recovery.

B.4 Additional regression results

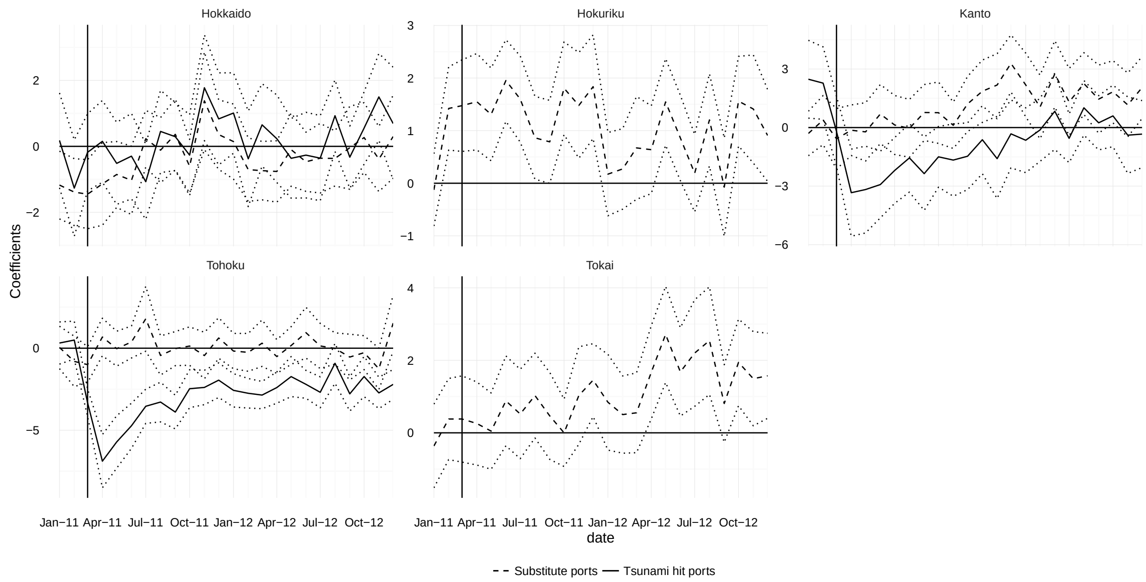
B.4.1 By Japanese region

Figure B-4: Results of Log export value and Extensive margin by Japanese regions

(a) Log export value



(b) Extensive margin



B.4.2 Varying substitute distance and selection

We present summary statistics of further robustness regressions in Table B-4. Figures that 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 well as decreasing their level of exposure, while adding to the counter-factuals 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 intensive margin and the trade share become statistically significant in the more restricted settings. These results further underline the conservative nature of our main estimates.

Adding Hokkaido as a treated region, rather designating its ports as counter-factual, changes little to our conclusions. On inspection we that including Hokkaido increases the standard errors 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 counter-factuals 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.[38]

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

Table B-4: Summary robustness results, port selection and placebo test

Model		Stat	EM	IM	lValue	TS
Exposure limited to 500km	hit	$\sum\beta$	-5.649^{***}	-2.056^{***}	-1.464^{***}	-0.312^{***}
		cse	0.195	0.149	0.080	0.041
	sub	$\sum\beta$	65.089^{***}	-3.809	4.983	-4.862
		cse	21.906	9.448	5.690	4.548
Exposure limited to 300km	hit	$\sum\beta$	-5.682^{***}	-2.066^{***}	-1.473^{***}	-0.317^{***}
		cse	0.209	0.148	0.082	0.042
	sub	$\sum\beta$	92.169^{**}	-15.121	2.604	-12.343^{*}
		cse	41.380	12.574	5.956	7.230
Exposure limited to 100km	hit	$\sum\beta$	-5.724^{***}	-2.065^{***}	-1.473^{***}	-0.303^{***}
		cse	0.223	0.133	0.088	0.034
	sub	$\sum\beta$	337.193	-86.840^{**}	86.188	-5.088
		cse	321.507	41.932	402.813	3.592
Add Hokkaido as treated	hit	$\sum\beta$	-24.603^{*}	-4.618	-4.568^{**}	-1.324^{*}
		cse	14.042	8.702	2.131	0.782
	sub	$\sum\beta$	7.267^{**}	2.487^{**}	1.217^{*}	0.144
		cse	2.836	1.229	0.698	0.426
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

Statistics are the sum of the first twelve months from March 2011 onwards. Standard errors 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 standard errors reperesent the mean and standard deviation over 500 repetitions. $p < 0.01\,^{***}$, $p < 0.05\,^{**}$, $p < 0.1\,^{*}$

Table B-5: Summary robustness results

Data	Model		Stat	lValue	lValue/prod
2-digit sector - Custom	fe	hit	$\sum\beta$	−6.414	−5.393
			cse	0.659***	0.496***
		sub	$\sum\beta$	1.203	1.526
			cse	1.103	0.933
	pd	hit	$\sum\beta$	−6.903	−6.336
			cse	0.805***	0.599***
		sub	$\sum\beta$	1.514	1.064
			cse	0.900*	0.602*
Custom	fe	hit	$\sum\beta$	−3.331	−1.743
			cse	0.923***	0.804**
		sub	$\sum\beta$	2.063	2.381
			cse	1.450	1.291*
	pd	hit	$\sum\beta$	−3.966	−3.170
			cse	1.141***	0.858***
		sub	$\sum\beta$	3.506	3.058
			cse	1.288***	0.926***
Prefecture	fe	hit	$\sum\beta$	−4.681	−3.378
			cse	1.004***	0.869***
		sub	$\sum\beta$	1.559	1.872
			cse	1.418	1.251
	pd	hit	$\sum\beta$	−4.333	−3.550
			cse	1.220***	0.956***
		sub	$\sum\beta$	3.327	2.877
			cse	1.349**	1.003***

Statistics are the sum of the first twelve months from March 2011 onwards. 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. Clusted Standard errors at the regional level are calculated using the delta method. Coefficients were transformed using $\exp(\beta) - 1$. Estimated following (12), with fixed effects (fe) or pre-differencing (pd) as indicates. $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *

B.4.3 Prefecture adjusted export value

We present additional results to Section 3.4. We divide exports by prefecture production at different levels of analysis, from the prefecture level to more detailed port-level exports. We aim to indicate the how strong the production factor affects our port-substition effect, as opposed to a firm-level substition effect. Table B-5 present the results. Note that for fixed effects models the inclusion of production increases the substitution effect, while for pre-differenced models it is decreased. However, it is possible to find statistically insignificant coefficients for the cummulative substitution effect by using a fixed-effect approach (rather than the pre-differencing) at the prefecture and 2-digit sector-port levels. However, this is not due to the inclusion of production as the same levels of significance are found for the in the column of Log export value, lValue.

B.5 Definition of sectors

We aggregate various HS-2-digits together to slightly reduce the number of sectors and create a more homogenous distributions on the number of product categories for each sector. The results are given in Table B-6. Doing makes sure that most sectors are represented in most ports in most time periods.

Table B-6: 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; sulphur; 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		
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		

Table B-6: Sector definitions, *continued*

HS code	HS name	n var	new sector	new n.var
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 fibres...	23		
54	Man-made filaments; strip and ...	133		
55	Man-made staple fibres	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		
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		