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

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**Abstract**

How do exports respond to changes domestic costs of bringing goods to ports? In particular how strongly are ports affected by changes in the cost of exporting at neighbouring ports? To answer these questions 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. This event allows us to measure the response of trade on ports not directly affected by the disaster. We detect a substitution effect for aggregate trade as well as differentiation at the sectoral level and by destination.

**Keywords:** firm heterogeneity, extensive margins, transportation costs, fixed costs

**JEL classification:** F14, O18, R1

## 1 Introduction

In this paper we contribute to the growing literature on internal barriers to international trade. We do this in two ways. First, we develop a theoretical framework based on a trade model with heterogeneous firms and multiple ports for exports. From a firms'

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perspective, each port will have a particular combination of fixed and variable cost. A profit maximising firm will minimise the cost of exports. We derive the implications for trade when fixed and variable costs change for one port and how this affect the trade for *other* ports. We hereby extend the gravity framework in heterogeneous firms model with internal trade costs and explicit interaction effects between trade routes. Secondly, we test the predictions of the theoretical model with Japanese customs data, exploiting the Great East Japan Earthquake of 2011 as a natural experiment.

The growing interest to internal barriers to trade comes when external barriers to trade have fallen dramatically over the last decades, and more progress and impact can be achieved by focusing on within country barriers relative to between countries (Clark et al., 2004; Allen and Arkolakis, 2014). Our paper informs what mechanisms are in play when policy makers decide to invest in trade infrastructure (e.g. roads, railways, domestic waters or sea ports) in one location, leaving other locations unchanged but potentially still impacted by spatial spillovers. One can also think of port competition in 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. That ports specifically are important for the facilitation of trade is well understood (Clark et al., 2004; Feenstra and Ma, 2014), while recent study indicated the importance of roads towards ports for the price of goods (Atkin and Donaldson, 2015).

The disaster that Japan experienced on 11 March 2011, albeit gruesome, is interesting from an economic point of view because, as we will substantiate further, the shock can be considered to be solely a supply shock on port-infrastructure with very little direct damage to firms on average over the time period that we consider. This is in contrast to earlier research on aggregate economic growth using natural disasters or firm level outcomes (e.g. Volpe Martinicus and Blyde, 2013) that could not distinguish between demand shocks for firms and supply shocks at the firm and regional level.[1]

Starting from the above observation, we build a model of multiple ports based on Melitz (2003). The number of ports in a country is exogenously given and ports from which heterogeneous firms export are differentiated with respect to their internal distance and specific fixed export costs. Some ports have their advantage in terms of proximity to firms' location while others are advantaged in terms of lower fixed export costs. Thus 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. All results collapse, however, by imposing absolute advantage for a specific port and we fall back to the case of single port as in a standard Melitz-type model.

[1]See Kirchberger (2017) for an overview of the economic literature on natural disasters

Motivated from an empirical point of view, we consider a special case in which firms are facing a choice to export between two competing ports that have different infrastructures summarised by the comparative advantage in costs, which we can designate as "tsunami hit ports" and "substitute ports". A third group of alternative ports are considered to be too far away to export from due to infinitely high internal trade cost. In the presence of the above mentioned port comparative advantage, we establish a port specific gravity equation and decompose trade flow of each port into extensive, intensive and composition margins of export as in Chaney (2008). We show that the aggregate trade flow is also subject to local transportation costs, which represents the distance between ports and firms' location. A rise in internal trade cost to a specific port induces a decrease in exports from that port while exports from the another competing port increases. Through such a substitution of export from one port to the another, aggregate exports of a country fluctuate to some extent. Therefore "Internal" gravity matters for aggregate trade flow. Changes in port specific fixed export costs also induces a similar substitution across ports, however, with different magnitude depending on comparative advantage of port.[2]

We aim to test the predictions on how ports are effected by the a change in internal trade costs, and whether there is a spill-over to other ports. For each Japanese sea port we have monthly data of exports by product group and destination from 2009 onwards. We calculate trade margins for each port using a 9-digit product categorisation, at the monthly frequency. We then exploit the 2011 Great Japanese Earthquake as an exogenous change in internal trade costs that affected some ports but not others. The tsunami following the earthquake destructed a number of ports off the North-Eastern Honshu coast, especially those directly in the line of the Tsunami. Other ports, further away, or protected by natural bays were much less or not affected by the natural disaster. We find the opposing effects on the two types of ports on the value of trade. When decomposing the trade flow in intensive and extensive margins we find that the effect mostly follows from the extensive margins of trade, as predicted by the theory. We find that the substitution ports may have gained up to 30% additional trade for some months and gained 3 percentage points in their extensive margin, representing a 10% increase from their pre-disaster margins.

Although we do use a natural disaster for our identification strategy our focus is different from many paper in the literature on the economic consequences of natural disasters. Firstly, we are also particularly interested on the effect of areas that were *not* hit by the disaster, which is often neglected in the existing research. Secondly, we argue that the destruction was limited to the coastal in north eastern Honshu, and did not

[2]Among a few theoretical paper that discuss internal trade costs, Forslid and Okubo (2015) argue that firm specific inter-regional iceberg cost has increasing return to scale in the framework of the footloose capital model. Their firm specific trade cost is similar to our port specific iceberg internal trade cost if we reinterpret the cost is firm specific rather than port specific. Corsetti and Dedola (2005) argue the presence of distribution cost within countries to investigate the non-traded component in the price of traded goods.

extend far inland. In a sense, the destruction was specifically targeted at ports only. Despite the dramatic images of inundated coastal villages, these presented local extremes that should not be held as representative for the entire region. 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 the 2011 disaster, in particular with respect to the consequences on the energy market following the failure of the Fukushima-Dashi Nuclear power plant has started. A collection of research to the energy implications is presented in (Economics of Energy & Environmental Policy, 2015).[3]

Closer to our work is Todo et al. (2015) who explore the role of local supply chain networks on firms recovery time after the earthquake using survey data. Our port-level exports data allows further insight on the role of supply chains through the substitution effect we document. Cole et al. (2015a) investigate the role of pre-disaster planning on post-disaster firm level performance. Studies that use firm level data are more limited on 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.

As stated, our paper fits in a new and growing literature in trade that focuses on the role of within-country barriers to trade (Hillberry and Hummels, 2007; Portugal-Perez and Wilson, 2012; Atkin and Donaldson, 2015). Closely related to ours is Volpe Martinicus and Blyde (2013) who test the effect of form level shipments following the 2009 earthquake in Chile that destroyed a large portion of the transport network. They find a significant reduction of trade from companies affected by damaged roads to transport their goods to sea- and airports, which were operational a few days after the earthquake. In contrast, in our case the major damage was precisely to ports rather than the transport network, we can more plausibly argue that firms were not severely affected or recovered very quickly and therefore we can explicitly look at the spill-over to other ports. In this way our estimates also reflect the resilience of a export infrastructure network in a developed economy that copes with an event that affects a fraction of the transport network. Furthermore, we develop a theoretical model that guides our estimates and gives an explanation to our findings, while also being in line with the results of Volpe Martinicus and Blyde (2013).[4] What we bring to this literature is a new extension to a familiar model of trade that can be directly brought to datasets such the one we present here while at the same time offer a case with a credible identification of exogenously changed fixed costs (for an extended period).

[3]Working papers of economics research using the 2011 Great Japanese Earthquake using firms' survey data include Cavallo et al. (2014) and Zhu et al. (2016)

[4]In unreported results, Volpe Martinicus and Blyde (2013, p. 160) do test for a spillover to other firms, but find no effects.

# 2 The model

We start from a general description of the theoretical model and explain the specific empirically motivated three port cases, namely tsunami hit and substitute ports relative to the rest, in the following subsection.

There are $N$ number of countries in the world. In a country $n$, there are multiple ports whose number is exogenously given by $K_n$. The population and labour supply is also exogenously given by $L_n$. In each country, sector 0 provides homogenous goods which serve as a *numéraire* and traded worldwide without any transportation cost while other sectors (whose total number is amount to $H$) are made of differentiated goods. Firms, that are heterogeneous in terms of their specific productivity level, are monopolistically competitive in differentiated sectors. Our model departs from Chaney (2008) by allowing firms to choose a specific port in exporting.

## 2.1 Households

Households of a typical country get a utility in consuming the set of differentiated product varieties in each sector, $\Omega_h$, as well as homogenous goods (omitting country 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, $c(\omega)$, is either produced locally or imported. The 'quality' of that good, $q(\omega)$, can be interpreted as an exogenous demand shifter. The elasticity of substitution of product varieties in each sector is given by $\sigma_h$ ($> 1$). The expenditure weight on homogenous goods is given by $\alpha_0$ and that on goods in sector $h$ is given by $\alpha_h$.

## 2.2 Ports and Firms

Firms are assumed to be heterogeneous in terms of their specific labour productivity level, $\varphi$, 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 a origin country $i$ to a destination country $j$ requires port specific fixed costs, $f^h_{ijk}$, and a port specific iceberg type of local transportation costs within country, $\mu^h_{ijk}$ ($> 1$), as well as an iceberg type of bilateral trade costs, $\tau^h_{ij}(> 1)$. From now on, we focus on a firm with a specific productivity, $\varphi$ and drop sector index $h$ when there is no room for confusion.

Total costs in producing $y$ unit of a good and exporting these goods to country $j$ from country $i$ of port $k$ is thus given by

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

where $w_i$ denotes real wages in country $i$ which is found to be 1 due to our choice of *numéraire* and $q_{ij}$ is origin-destination (-sector) specific demand shifter.[5] $Z_i$ represents the level of labor productivity, which is common for all firms in country $i$.

## 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 $\varphi$ from a destination country $j$ is given by

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

with

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

In the above expression, $P_j$ is the ideal price index for a particular sector in country $j$.

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 corrects 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:

[5] We do not model the endogenous product quality choice by firm and consider it as exogenous for the sake of simplicity. See Feenstra and Romalis (2014) for instance about its endogenous determination mechanism based on Melitz (2003).

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

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 $\mu_{ijk}$ and port specific fixed export costs $f_{ijk}$.

Having computed the cutoff productivity level for each port, we rank them according to their size as

$$\overline{\varphi}_{ijK_n} < \overline{\varphi}_{ijK_n-1} < ... < \overline{\varphi}_{ij2} < \overline{\varphi}_{ij1} \quad (5)$$

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

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

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. We assume that port $s$ is more efficient in terms of local transportation costs while port $s$ is less efficient in terms of its fixed export costs than port $k$. Under such a condition, firms are spread into multiple ports in exporting. Precisely speaking, by assuming *the port comparative advantage* as $f_{ijs}/f_{ijk} > (\mu_{ijs}/\mu_{ijk})^{1-\sigma} > 1$, we establish the following proposition.

**Proposition 1** .

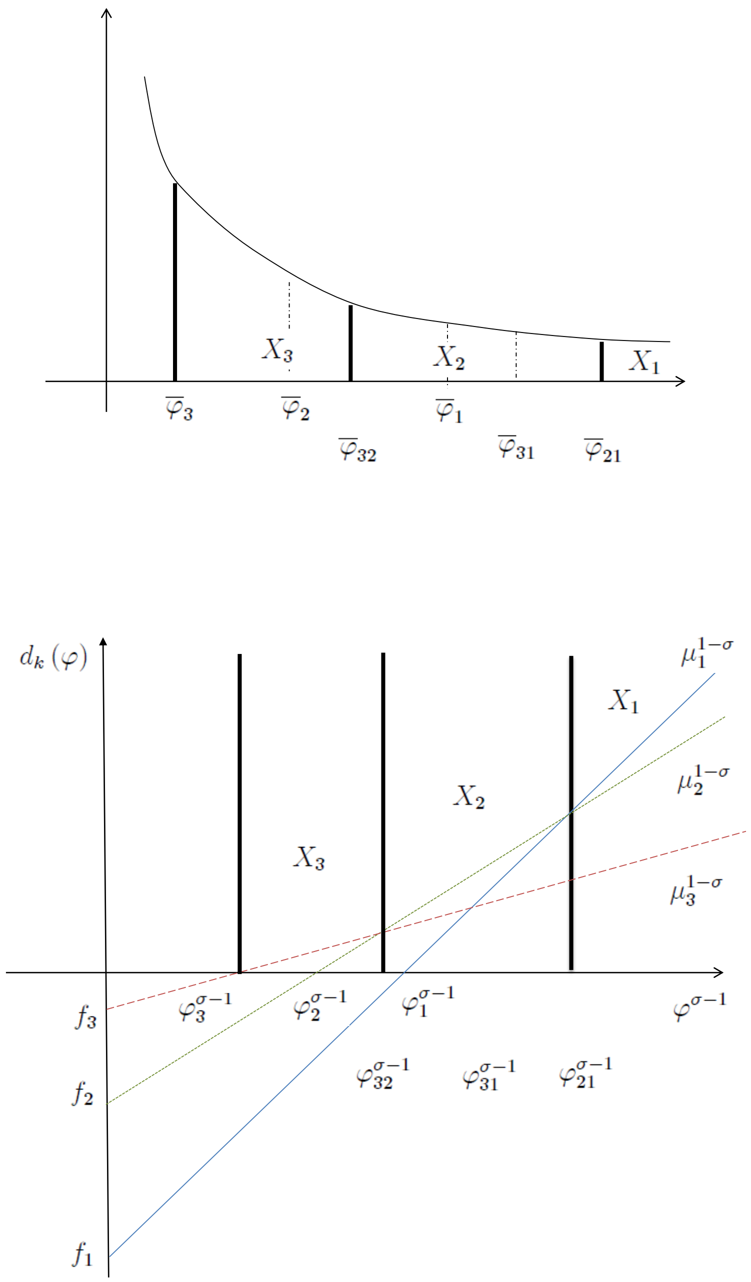
*Under $f_{ijs}/f_{ijk} > (\mu_{ijs}/\mu_{ijk})^{1-\sigma} > 1$ for $k = 2...K_n$ with $k > s$, we have $\overline{\varphi}_{ijk} < \overline{\varphi}_{ijs} < \overline{\varphi}_{ijks}$. In this case, firms with $\overline{\varphi}_{ijks} < \varphi$ prefer to export from port $s$ while firms with $\varphi < \overline{\varphi}_{ijks}$ prefer to export from port $k$ and multiple ports are in action.*

**Proof.** See Appendix A. ■

When $(\mu_{ijs}/\mu_{ijk})^{1-\sigma} > 1$, 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 the ranking of zero profit cutoff productivity levels for each port as (5), the firm with $\varphi$ eventually chooses to export from one specific port $k^*$ that maximises its exporting profits $d_{ijk^*}(\varphi_{ijk^*})$. See also Figure 1 where we provide a specific case with $K_n = 3$ and $\overline{\varphi}_{32} < \overline{\varphi}_{31} < \overline{\varphi}_{21}$.

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

Figure 1: Multiple Port in Action ($K_n = 3$ and $\overline{\varphi}_3 2 < \overline{\varphi}_3 1 < \overline{\varphi}_2 1$)



**Corollary 1** *When $\mu_{ij1} > \mu_{ij2} > ... > \mu_{ijK_n-1} > \mu_{ijK_n}$, all exporters export from port $K_n$.*

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

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

$$\left(\frac{\sigma-1}{\sigma}P_j\right)^{1-\sigma} = \sum_{m=1}^{N} w_m L_m \left[\int_{\overline{\varphi}_{mjK_n}}^{\overline{\varphi}_{mjK_nK_n-1}} \left(\frac{w_m \mu_{mjK_n} \tau_{mj}}{q_{mj} Z_m}\right)^{1-\sigma} dG(\varphi) + \cdots + \int_{\overline{\varphi}_{mj21}}^{\infty} \left(\frac{w_m \mu_{mj1} \tau_{mj}}{q_{mj} Z_m}\right)^{1-\sigma} dG(\varphi)\right] \tag{7}$$

## 2.5 Tsunami Hit ($\gamma$) and Substitute ($\delta$) Port

In order to solve the model, we assume Pareto distribution for firm specific productivity level as $G(\varphi) = 1 - \varphi^{-\kappa}$ where $\kappa$ ($> \sigma - 1$) is the shaping parameter of distribution. When $\kappa$ increases, firms are more concentrated at its minimum level of productivity, which we set as unity. Also, we assume that $\mu_{ijK_n-2} = \infty$ which results in $\overline{\varphi}_{ijK_n-2} = \infty$. The above condition eliminates the possibility of exporting from ports with $k \geq K_n - 2$ which are 'too far' leaving the possibility to firms to export either from port $K_n$ or $K_n - 1$. This latter assumption is motivated from practical point of view that firms are facing the choice between two alternatives of ports in exporting. From now on, port $K_n - 1$ and port $K_n$ are designated as port $\gamma$ and port $\delta$, respectively. Port $\gamma$ is considered as 'tsunami hit' port allowing a limited number of firms at the higher end of distribution to export while $\delta$-port is considered as 'substitute' port attracting the majority of firms at the lower end of distribution. In this interpretation negative shocks on port specific fixed cost and/or port specific internal trade cost at the tsunami hit port induces port substitution among heterogeneous firms but no exit of firms from international exports. Therefore, this configuration describes well what happened with the GEE in which only Tohoku region was hit by tsunami and aggregate export activity was not damaged.

Provided the above distribution and plugging the cutoff levels (4) and (6) in the ideal price index (7) together with the definition of substitute ($\delta$) and hit ($\gamma$) port, we have

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

where $\lambda_2 = \left[(1+d)/Y\right]\left[\kappa - (\sigma-1)/\kappa\right]\left[\sigma/(\sigma-1)\right]^{\kappa}(\sigma/\alpha)^{\frac{\kappa}{\sigma-1}-1}$ and

$$\vartheta_j^{-k} =$$

$$\sum_{m=1}^{N} \frac{Y_m}{Y} \left( \frac{w_m \tau_{mj}}{q_{mj} Z_m} \right)^{-\kappa} \left[ f_{mj\delta}^{-\left(\frac{\kappa}{\sigma-1}-1\right)} \mu_{mj\delta}^{-\kappa} + \left(f_{mj\gamma} - f_{mj\delta}\right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)} \left( \mu_{mj\gamma}^{-(\sigma-1)} - \mu_{mj\delta}^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}} \right]. \tag{8}$$

Thus $\vartheta_j$ 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 $m$ is considered to be negligible in $\vartheta_j$. Similarly, we assume that any changes in port specific costs are negligible as $\partial\vartheta_j/\partial f_{mj\gamma} = \partial\vartheta_j/\partial f_{mj\delta} = \partial\vartheta_j/\partial\mu_{mj\gamma} = \partial\vartheta_j/\partial\mu_{mj\delta} = 0$.

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

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

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

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

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

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

## 2.6 Gravity

Exports from tsunami hit port $\gamma$ is given by $X_{ij\gamma} = w_i L_i \int_{\overline{\varphi}_{ij\delta\gamma}}^{\infty} x_{ij\gamma}(\varphi)\, dG(\varphi)$ while those from substitute port $\delta$ is given by $X_{ij\delta} = w_i L_i \int_{\overline{\varphi}_{ij\delta}}^{\overline{\varphi}_{ij\delta\gamma}} x_{ij\delta}(\varphi)\, dG(\varphi)$. Thanks to the closed form expression, we derive gravity equation from each port. Exports from port $\gamma$ is given by

$$X_{ij\gamma} = \alpha \frac{Y_i Y_j}{Y} \left( \frac{w_i \tau_{ij}}{q_{ij} Z_i \vartheta_j} \right)^{-\kappa} \mu_{ij\gamma}^{-(\sigma-1)} \left( \mu_{ij\gamma}^{-(\sigma-1)} - \mu_{ij\delta}^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}-1} \left( f_{ij\gamma} - f_{ij\delta} \right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)}. \quad (10)$$

Exports from port $\delta$ is given by

$$X_{ij\delta} = \alpha \frac{Y_i Y_j}{Y} \left( \frac{w_i \tau_{ij}}{q_{ij} Z_i \vartheta_j} \right)^{-\kappa}$$
$$\left[ \mu_{ij\delta}^{-\kappa} f_{ij\delta}^{-\left(\frac{\kappa}{\sigma-1}-1\right)} - \mu_{ij\delta}^{-(\sigma-1)} \left( \mu_{ij\gamma}^{-(\sigma-1)} - \mu_{ij\delta}^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}-1} \left( f_{ij\gamma} - f_{ij\delta} \right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)} \right]. \quad (11)$$

Total exports from country $i$ to $j$ is thus given by

$$X_{ij} = X_{ij\delta} + X_{ij\gamma}$$
$$= \alpha \frac{Y_i Y_j}{Y} \left( \frac{w_i \tau_{ij}}{q_{ij} Z_i \vartheta_j} \right)^{-\kappa} \left[ \mu_{ij\delta}^{-\kappa} f_{ij\delta}^{-\left(\frac{\kappa}{\sigma-1}-1\right)} - \left( \mu_{ij\gamma}^{-(\sigma-1)} - \mu_{ij\delta}^{-(\sigma-1)} \right)^{\frac{\kappa}{\sigma-1}} \left( f_{ij\gamma} - f_{ij\delta} \right)^{-\left(\frac{\kappa}{\sigma-1}-1\right)} \right].$$

Note that by abandoning the assumption of $\mu_{ij\delta} > \mu_{ij\gamma}$, all firms export from substitute port $\delta$ 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 $X_\gamma = N_{X\gamma} \widetilde{x}_\gamma$ and $X_\delta = N_{X\delta} \widetilde{x}_\delta$ where $N_{X\gamma} = wL \left(1 - G(\overline{\varphi}_{\delta\gamma})\right)$ and $N_{X\delta} = wL \left(G(\overline{\varphi}_{\delta\gamma}) - G(\overline{\varphi}_\delta)\right)$ represent the number exporters and

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

and

$$\widetilde{x}_\delta = \left[ \int_{\overline{\varphi}_\delta}^{\overline{\varphi}_{\delta\gamma}} x_\delta(\varphi)\, dG(\varphi) / \left(G(\overline{\varphi}_{\delta\gamma}) - G(\overline{\varphi}_\delta)\right) \right]$$

capture the average export flow among these exporters from tsunami hit port $\gamma$ and substitute port $\delta$, respectively. The number of exporters is called 'extensive margins.' The average export flow is further decomposed into 'intensive margins,' i.e. changes in average export scale given a cutoff productivity level and 'composition margins,' i.e. remaining impact on average export flow induced by changes in 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 $\tau$, aggregate labor productivity

Table 1: Margins Decomposition

| Elasticities | E.M. | I.M. | C.M. | Total |
|---|---|---|---|---|
| $d\ln X_\gamma/d\ln\tau$ | $-\kappa$ | $-(\sigma-1)$ | $\sigma-1$ | $-\kappa$ |
| $d\ln X_\gamma/d\ln Z_i$ | $\kappa$ | $\sigma-1$ | $-(\sigma-1)$ | $\kappa$ |
| $d\ln X_\gamma/d\ln q$ | $\kappa$ | $\sigma-1$ | $-(\sigma-1)$ | $\kappa$ |
| $d\ln X_\gamma/d\ln f_\gamma$ | $-\frac{\kappa}{\sigma-1}\mathsf{F}_\gamma$ | $0$ | $\mathsf{F}_\gamma$ | $-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_\gamma$ |
| $d\ln X_\gamma/d\ln f_\delta$ | $\frac{\kappa}{\sigma-1}\mathsf{F}_\delta$ | $0$ | $-\mathsf{F}_\delta$ | $\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_\delta$ |
| $d\ln X_\gamma/d\ln\mu_\gamma$ | $-\kappa\mathsf{U}_\gamma$ | $-(\sigma-1)$ | $(\sigma-1)\mathsf{U}_\gamma$ | $-[\kappa-(\sigma-1)]\,\mathsf{U}_\gamma-(\sigma-1)$ |
| $d\ln X_\gamma/d\ln\mu_\delta$ | $\kappa\mathsf{U}_\delta$ | $0$ | $-(\sigma-1)\mathsf{U}_\delta$ | $[\kappa-(\sigma-1)]\,\mathsf{U}_\delta$ |
| $d\ln X_\delta/d\ln\tau$ | $-\kappa$ | $-(\sigma-1)$ | $\sigma-1$ | $-\kappa$ |
| $d\ln X_\delta/d\ln Z_i$ | $\kappa$ | $\sigma-1$ | $-(\sigma-1)$ | $\kappa$ |
| $d\ln X_\delta/d\ln q$ | $\kappa$ | $\sigma-1$ | $-(\sigma-1)$ | $\kappa$ |
| $d\ln X_\delta/d\ln f_\delta$ | $-\frac{\kappa}{\sigma-1}\mathsf{\Gamma}_\delta$ | $0$ | $-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{\Delta}_\delta+\frac{\kappa}{\sigma-1}\mathsf{\Gamma}_\delta<0$ | $-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{\Delta}_\delta$ |
| $d\ln X_\delta/d\ln f_\gamma$ | $\frac{\kappa}{\sigma-1}\mathsf{\Gamma}_\gamma$ | $0$ | $\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{\Delta}_\gamma-\frac{\kappa}{\sigma-1}\mathsf{\Gamma}_\gamma>0$ | $\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{\Delta}_\gamma$ |
| $d\ln X_\delta/d\ln\mu_\delta$ | $-\kappa\mathsf{\Theta}_\delta$ | $-(\sigma-1)$ | $-[\kappa-(\sigma-1)]\,\mathsf{\Lambda}_\delta+\kappa\mathsf{\Theta}_\delta<0$ | $-[\kappa-(\sigma-1)]\,\mathsf{\Lambda}_\delta-(\sigma-1)$ |
| $d\ln X_\delta/d\ln\mu_\gamma$ | $\kappa\mathsf{\Theta}_\gamma$ | $0$ | $[\kappa-(\sigma-1)]\,\mathsf{\Lambda}_\gamma-\kappa\mathsf{\Theta}_\gamma>0$ | $[\kappa-(\sigma-1)]\,\mathsf{\Lambda}_\gamma$ |

Trade effects by port, $k=\gamma,\delta$, for various exogenous shocks: $\tau$ international trade costs, $Z_i$ labour productivity in country $i$, $q$ quality or demand shifter, $f_k$ port specific fixed costs, $\mu_k$ 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.)

Table 2: Parameters

| | |
|---|---|
| $\overline{f}_\gamma>0,\ \overline{f}_\delta>0,\ \overline{\mu}_\gamma>0,\ \overline{\mu}_\delta>0$ | $\overline{f}_\gamma/\overline{f}_\delta>\left(\overline{\mu}_\gamma/\overline{\mu}_\delta\right)^{\sigma-1}>1$ |
| $\mathsf{F}_\gamma=\frac{1}{1-\frac{\overline{f}_\delta}{\overline{f}_\gamma}}>1$ | $\mathsf{F}_\delta=\frac{1}{\frac{\overline{f}_\gamma}{\overline{f}_\delta}-1}>0$ |
| $\mathsf{F}_\gamma>\mathsf{U}_\gamma=\frac{1}{1-\left(\frac{\overline{\mu}_\gamma}{\overline{\mu}_\delta}\right)^{\sigma-1}}>1$ | $\mathsf{U}_\delta=\frac{1}{\left(\frac{\overline{\mu}_\delta}{\overline{\mu}_\gamma}\right)^{\sigma-1}-1}>\mathsf{F}_\delta>0$ |
| $\mathsf{\Gamma}_\delta=\frac{1}{1-\left(\frac{\mathsf{F}_\delta}{\mathsf{U}_\delta}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\mathsf{F}_\delta}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}}-1}>1$ | $\mathsf{\Delta}_\delta=\frac{1}{1-\left(\frac{\mathsf{F}_\delta}{\mathsf{U}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\mathsf{F}_\delta}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>1$ |
| $\mathsf{\Theta}_\delta=\frac{1}{1-\left(\frac{\mathsf{F}_\delta}{\mathsf{U}_\delta}\right)^{\frac{\kappa}{\sigma-1}}}+\frac{\mathsf{U}_\delta}{\left[\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}}-1\right]}>1$ | $\mathsf{\Lambda}_\delta=\frac{1}{1-\left(\frac{\mathsf{F}_\delta}{\mathsf{U}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}}+\frac{\mathsf{U}_\delta}{\left[\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}-1\right]}>1$ |
| $\mathsf{\Gamma}_\delta>\mathsf{\Gamma}_\gamma=\frac{\mathsf{F}_\gamma}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}}-1}>0$ | $\mathsf{\Delta}_\delta>\mathsf{\Delta}_\gamma=\frac{\mathsf{F}_\gamma}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$ |
| $\mathsf{\Theta}_\delta>\mathsf{\Theta}_\gamma=\frac{\mathsf{U}_\gamma}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}}-1}>0$ | $\mathsf{\Lambda}_\delta>\mathsf{\Lambda}_\gamma=\frac{\mathsf{U}_\gamma}{\left(\frac{\mathsf{U}_\delta}{\mathsf{F}_\delta}\right)^{\frac{\kappa}{\sigma-1}-1}-1}>0$ |

level $Z_i$, country and destination specific demand shifter $q$, port specific fixed export costs $f_k$ and port specific local transportation costs $\mu_k$. 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 $k=\gamma$ or $\delta$, $v=\tau$, $Z_i$, $q$, $f_k$, $\mu_k$ 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 $\gamma$ and substitute port $\delta$, respectively. In Table 1, $\overline{f}_\gamma$, $\overline{f}_\delta$, $\overline{\mu}_\gamma$ and $\overline{\mu}_\delta$ represent the steady state value of port specific fixed costs and local transportation costs. Capital letters in Table 1 are a function of parameters given these steady state values which are detailed in Table 2.

As shown in Table 1, shocks that are independent of port characteristics, namely $\tau$, $Z_i$ and $q$, have exactly the same impact on exports from port $\gamma$, $X_\gamma$ and those from port $\delta$, $X_\delta$ as well as for each margin. Such a symmetry across two ports is true for margin decomposition induced by other two shocks, $Z_i$ and $q$. For instance, when bilateral trade costs $\tau$ 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 $\gamma$ and substitute port $\delta$. The same expression is provided by Chaney (2008) with a single port case.

Port specific shocks, however, have dramatically different implications across ports. On the one hand, with respect to trade flow $X_\gamma$, when fixed export costs $f_\gamma$ increase, extensive margins decrease by $-\frac{\kappa}{\sigma-1}\mathsf{F}_\gamma$ and composition margins increase by $\mathsf{F}_\gamma$. This is because a number of less productive firms substitute from tsunami hit port $\gamma$ to substitute port $\delta$ in exporting following such a rise in $f_\gamma$. Total impact on export $X_\gamma$ is thus given by $-\left(\frac{\kappa}{\sigma-1}-1\right)\mathsf{F}_\gamma$. Since $\mathsf{F}_\gamma > 1$, 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 $f_\gamma$, extensive margins of substituting port $\delta$ increase by $\frac{\kappa}{\sigma-1}\Gamma_\gamma$ and composition margins increases by $\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_\gamma - \frac{\kappa}{\sigma-1}\Gamma_\gamma$. As a result total exports $X_\delta$ increase by $\left(\frac{\kappa}{\sigma-1}-1\right)\Delta_\gamma$. This is due to the above mentioned port substitution effect through which some exporters switch from tsunami hit port $\gamma$ to substitute port $\delta$ in exporting following a rise in fixed export costs in tsunami hit port $\gamma$, $f_\gamma$. The similar argument holds for a rise in fixed export costs in substitute port $\delta$, $f_\delta$ with different degree of substitution effect, however.

When local transportation costs until port $\gamma$, $\mu_\gamma$ increase, exporters switch from tsunami hit port $\gamma$ to substitute port $\delta$ in exporting. As a result, total exports decrease in tsunami hit port $\gamma$, $X_\gamma$ by $-[\kappa-(\sigma-1)]\mathsf{U}_\gamma-(\sigma-1)$ while total exports in substitute port $\delta$, $X_\delta$ increase by $[\kappa-(\sigma-1)]\Lambda_\gamma$. In achieving such a change in $X_\gamma$, the number of exporters decrease by $-\kappa\mathsf{U}_\gamma$, intensive margins decrease by $-(\sigma-1)$ while composition margins increase by $(\sigma-1)\mathsf{U}_\gamma$ in tsunami hit port $\gamma$. Since $\mathsf{U}_\gamma > 1$, the size of change of each margin is amplified compared to the case with a rise in international bilateral trade costs $\tau$. And we have a mirror image for each margin in competing substitute port $\delta$ where total exports rise by $[\kappa-(\sigma-1)]\Lambda_\gamma$ through rise in extensive margins by $\kappa\Theta_\gamma$ and changes in composition margins by $[\kappa-(\sigma-1)]\Lambda_\gamma - \kappa\Theta_\gamma$. The similar argument holds for a rise in local transportation costs until substitute port $\delta$, $\mu_\delta$ with different degree of substitution effect, however.

## 2.8 Numerical Simulation

Here we calibrate the theoretical model and provide the results of a numerical simulation. The parameter value of the elasticity of substitution and the extent of product heterogeneity are set as $\sigma = 6$ and $\kappa = 10$, respectively. These values are standard and in line with the literature. The steady state level of port specific fixed cost and internal transportation cost of each tsunami hit $\gamma$ and substitute $\delta$ port are found based on the pre-mean values of tsunami hit ports and substitute ports following the Great Japan East Earthquake.[6]

Having in mind a port and road destruction in Tohoku region following the GEE, in Table 3 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 $f_\gamma$ and $\mu_\gamma$, respectively.[7] First, following a one percentage points increase in $f_\gamma$, due to a larger steady state size of $\delta$ (substitute) ports compared to $\gamma$ (hit) ports in terms of export share ($X_\gamma/X_\delta = 0.106$), extensive margins ($EM_\gamma/EM_\delta = 0.347$) and intensive margins ($IM_\gamma/IM_\delta = 0.712$), there is a smaller adjustment for substitute $\delta$ port in all types of margins as well as total export. For instance, extensive margins decrease by $-5.66$ percentage points for tsunami hit $\gamma$ port while those for substitute $\delta$ port increases by 1.66 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 2.06 percentage point following $f_\gamma$ shock, respectively. This is due to a substitution effect across port 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 cost shock, $\mu_\gamma$ but with a larger magnitude.

Figure 2 shows the results of the sensitivity analysis against the elasticity of substitution, $\sigma$.[8] The first column in the figure shows the results for $f_\gamma$ shock for each tsunami hit and substitute port as well as aggregate flow. For extensive margins, with a lower value of $\sigma$, there exists a stronger negative adjustment in tsunami hit $\gamma$ port. On the other hand, a stronger positive adjustment appears with a higher value of $\sigma$ for substitute $\delta$ port following the same shock. However, such a non-linearity disappear for intensive and composition margins and the adjustments are insensitive with respect to the value of $\sigma$

[6] Namely, we find the steady state value of $f_\gamma$, $\mu_\gamma$ and $\mu_\delta$ 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, there are $X_\gamma/X_\delta = 0.22/2.08$, $EM_\gamma/EM_\delta = 8.99/25.91$ and $IM_\gamma/IM_\delta = 3.07/4.31$ which are summarised in Table 4 in the empirical section. The above procedure gives $\overline{f}_\gamma = 1.5471$, $\overline{\mu}_\gamma = 1.0698$, $\overline{\mu}_\delta = 1.1206$ while we set $\overline{f}_\delta = 1$ without loss of generality at the initial steady state.

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

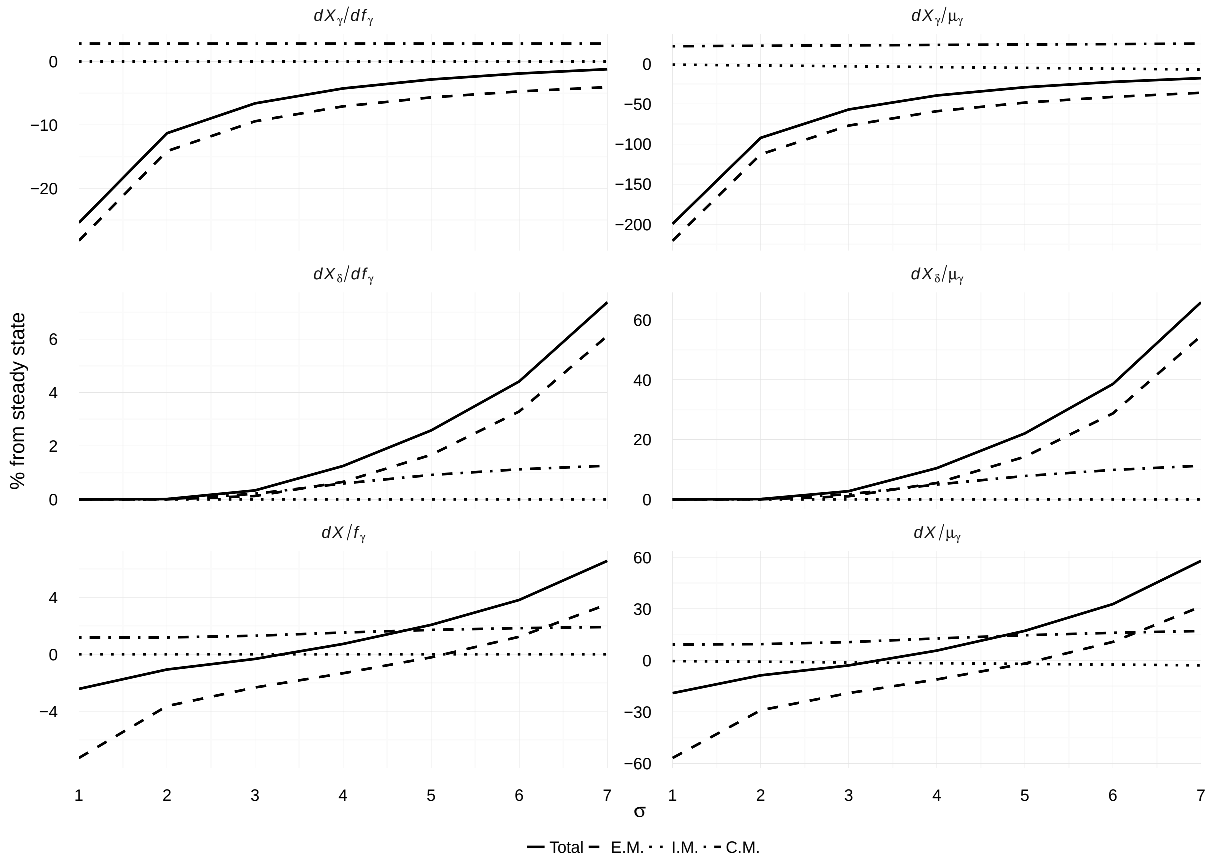
[8] In computing Figure 2, we fix $\kappa$ and $f_\gamma$, $f_\delta$, $\mu_\gamma$ and $\mu_\delta$ as 3. Restriction on parameters that allows a multiple port structure argued in the proposition 1 is satisfied in the figure.

Table 3: Margins Decomposition

| Elasticities | E.M. | I.M. | C.M. | Total |
|---|---|---|---|---|
| $d \ln X_\gamma / d \ln f_\gamma$ | $-5.66$ | 0.00 | 2.83 | $-2.83$ |
| $d \ln X_\delta / d \ln f_\gamma$ | 1.66 | 0.00 | 0.91 | 2.58 |
| $d \ln X / d \ln f_\gamma$ | $-0.22$ | 0.00 | 1.71 | 2.06 |
| $d \ln X_\gamma / d \ln \mu_\gamma$ | $-48.33$ | $-5.00$ | 24.16 | $-29.13$ |
| $d \ln X_\delta / d \ln \mu_\gamma$ | 14.23 | 0.00 | 7.80 | 22.03 |
| $d \ln X / d \ln \mu_\gamma$ | $-1.89$ | $-2.08$ | 14.61 | 17.13 |

Simulation results for both ports of a shock to a tsunami hit ($\delta$) port represented by its fixed $f_\gamma$ and variable $\mu_\gamma$ cost. Effects measured in percentage points deviations from steady state following a 1% shock. Steady state margins based on empirical margins of Japanese ports, see main text for further underlying assumptions.

Figure 2: Sensitivity Analysis on $\sigma$




Simulation results for both ports of a shock to a tsunami hit ($\delta$) port represented by its fixed $f_\gamma$ and variable $\mu_\gamma$ cost. Effects measured in percentage points deviations from steady state following a 1% shock. Steady state margins based on empirical margins of Japanese ports, see main text for further underlying assumptions.

for both types of port. The second column in the figure shows the result for $\mu_\gamma$ shock where we find a similar result but with a larger magnitude.[9]

# 3 Empirics

## 3.1 Identification strategy

The theoretical model, following equations (10) and (11), suggests the following linearized equation of exports,

$$\ln X_{ijk} = \ln \frac{Y_i}{Y} + \ln \frac{Y_j}{Y} - \kappa \ln \tau_{ij} + \kappa \ln M_i + \kappa \ln \vartheta_j + a \ln \mu_{ijk} + b \ln \mu_{ijl} + c \ln f_{ijk} + d \ln f_{ijl}$$

for exports $X$ from port $k$ in country $i$ to country $j$. One can add a subscript $h$ for each variable to capture the different effects at the sectoral level. We are particularly interested identifying the effects of changes in the variable and fixed costs on the export level of ports and their decomposition of the margins. We propose to use the event of the earthquake and tsunami of March 2011 that struck the north-east coast of Japan as an exogenous variation in the cost of bringing goods to port for exports. The tsunami caused destruction for some ports at a specific point in time and therefore leads to the potential of other ports to be affected through the trade spill-over that we modelled, while not themselves directly affected by the earthquake and tsunami.

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 of magnitude 9, the strongest recorded for Japan ever, with the epicentre 70 km from the coast at a depth of 30 km. The earthquake was followed by dozens of smaller quakes of 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, although these were local extremes.

Although devastating we argue that the destruction 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. In order to give further backing to this argument we calculated two measures that should indicate how much of the regional economies was directly affected by the tsunami. One measure is based on building structures identified on OpenStreetMaps, and another is based on satellite land cover data.[10] Both measures give similar results, in the Tohoku region around 5% of industrial and commercial land was affected by floods, while the

[9] The results for other types of shock and those obtained with the sensitivity analysis of different values of $\kappa$ are available upon request.

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

relevant number for the Kanto region is much lower at 0.12% to 0.01% depending on the measure used. [11] These numbers also correspond with similar figures reported by Todo et al. (2015) and Cole et al. (2015a).[12]

The tsunami was unexpected and struck 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'.

Figure 3 presents a map of northern Japan giving an overview of the ports that were hit by the March 2011 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 circles denotes the various ports in the Tokyo area and the Fukushima-Dachi 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 Industry we have the recorded wave heights for each port (Ministry of Land, Infrastructure, Transport and Tourism, 2011). The ports closest to the earthquake epicentre were hit by the highest waves.

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.

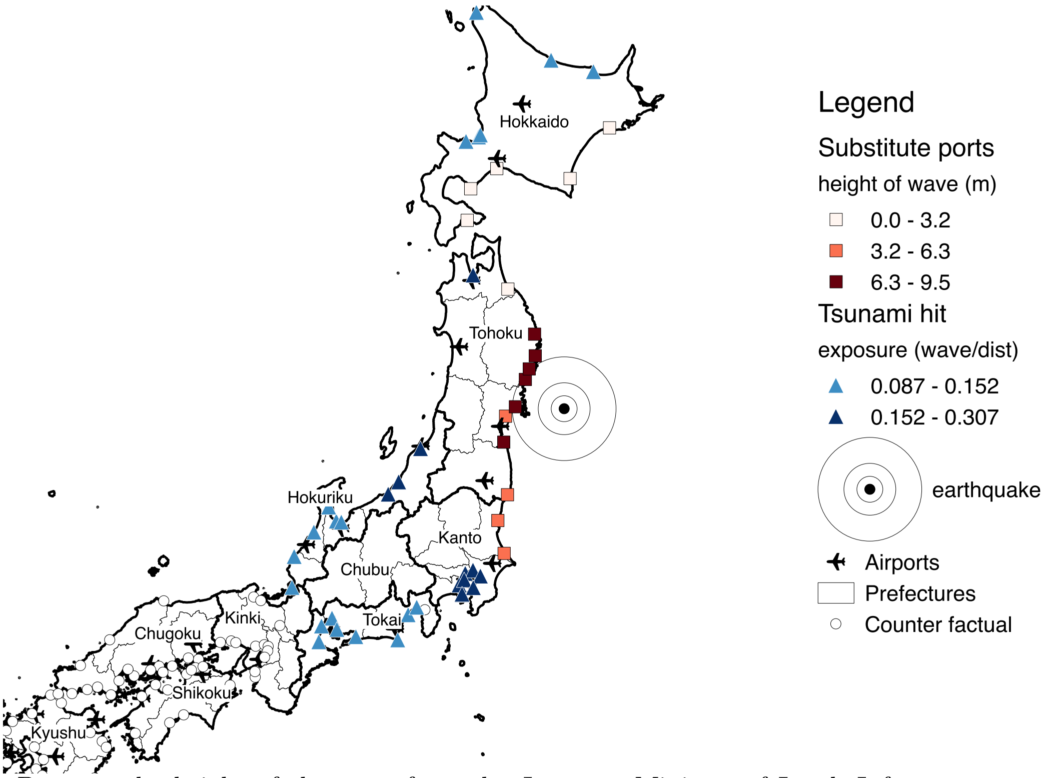
As further substitutes we find that ports in the Hokoriku and Tokai region may also be close enough to be impacted. The northern island Hokkaido is a special case. As a separate island with no road links (there is a train tunnel from Aomori, at the north of Honshu, to Hakodate on Hokkaido) it is unlikely 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 destruction. We will explore this further in the empirical section.

The ports that were protected through natural bays or otherwise not directly facing

[11] 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.

[12] 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). Below, we will still present robustness results that control for prefecture level industrial output.

Figure 3: Tsunami-hit and substitute ports




Note: Data on the height of the wave from the Japanese Ministry of Land, Infrastructure, Transport and Tourism (2011), the location of the earthquake from the US Geological Survey, exposure authors' calculations. In the regressions Hokkaido ports are not designated as treated.

the earthquake's epicentre turn out as substitutes with level of potential substitution varying with distance and the wave height of the ports that were struck. We find that the potential substitutes are mostly to be found in the Tohoku and Kanto regions, and further in Hokuriku and Tokai. The color coding of the substitution ports (triangles) indicates a level of exposure based on the function defined below. Essentially, it gives a measure of how close a port is to a port that was hit by the tsunami, while taking into account the variation of wave height over the coast line.

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.

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

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

with subscripts as in the theoretical model, $k$ and $l$ for port, $h$ for sector and $t$ for time. The tsunami is an event that can be tracked over time and geography (and sectors only in combination with the specific ports, further discussed below), while 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 destruction will affect ports differently depending 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 $\mu_k$, $\mu_l$, $f_k$ and $f_l$ (omitting subscripts $i$ and $j$).

There is *a priori* no clear way to disentangle those two effects. 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 destruction 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 port *construction* or upgrades on exports we imagine that it it does not only affect the site of the port itself but also its direct surroundings. 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. What we are estimating therefore is the average aggregate effect of such changes.

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 destruction 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 infrastructure process. What also matters here is that ports were rebuild after the disaster and we take that period into account. So just as much as we can analyse the immediate impact, 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

$$\begin{aligned} \ddot{y}_{k,g,t} &= \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{1,\tau} \mathrm{I}(\text{hit}_k) + \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{2,\tau} \mathrm{I}(\text{sub}_{k,g}) + \epsilon_{k,g,t} \\ & \quad k = 1, \ldots, 119;\ g = h \text{ or } m,\ t = \text{Jan 2011},\ldots,\text{Dec 2012} \end{aligned} \tag{12}$$

keeping with the notation of the theoretical model, $k$ for port, $g$ for group, such as sectors

$h$ or destinations $m$, and finally time $t$. The left hand side variable $\ddot{y}_{k,g,t}$ will be any trade variable of interest. The indicator functions $\mathrm{I}(\mathrm{hit}_k)$ and $\mathrm{I}(\mathrm{sub}_{k,g})$ designate those port-group combinations that are treated by the tsunami or as substitute. For the tsunami hit ports the indicator varies only at the port level since all products will be affected. However, for the substitute ports assume treatment takes place at the port-group level. For instance, if the group is taken as product sector categories, only products belonging to the sectors that were exported from a tsunami hit port will be substitute, with others unaffected. Geographically, the designation for substitute is defined as being located in one of the four regions where ports have the highest potential exposure (while not being hit by a tsunami themselves).

The parameters of interest are collected in the $\beta_{1,\tau}$'s and $\beta_{2,\tau}$'s. 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: $\beta_{1,\tau} = a+c$ and $\beta_{2,\tau} = b+d$. In combination with the indicator functions $\mathrm{I}(\mathrm{hit}_k)$ and $\mathrm{I}(\mathrm{sub}_{k,g})$, 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 potential exposed to substitution. Through this setup, the effect of interest is estimated as compared 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.

As was indicated before, the ports are geographically clustered. Apart from that there might be other characteristics that are port specific but time constant (at least over the few years we are analysing) such as the characteristics of industry in the region that it services. Similarly, we like to control for sectoral effects (when analyses includes the sectoral dimension) and capture some effect of seasonality, which may be relevant for the monthly frequency of the data. Typically we would include a set of fixed effects that could be characterised as $\alpha_k + \gamma_h + \theta_{\mathrm{month}}$, or some interactive combination of these.[13]

Since the size of the shock from the earthquake and tsunami can be quite large and persistent for those ports that are hit, while potentially small for the ports that serve as substitute using a normal fixed effect procedure would filter out the variation that we want to explore. These fixed effects demean the variables using the entire time-span of the data. Since the period prior to the tsunami is shorter than the period after this demeaning procedure could potentially filter out too much variation of interest from the period post-tsunami.

Instead, the outcome variable $\ddot{y}_{k,g,t}$ will be the pre-differenced transformation of $y_{k,g,t}$. The pre-differencing comes in place of fixed effects in the regression. We subtract from the outcome variables a constant (over time) that is calculated as the average at the

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

port-sector-month level using pre-2011 data.[14] Therefore we choose instead to demean the outcome variables using only data from before the tsunami. With the calculation of the standard errors we make an adjustment in the degrees of freedom to correctly take into account this pre-differencing. The port-sector level demeans the outcome variables over the port size and specialisation, while the interaction with the month adjusts for potential seasonal effects.

We can control for the wide range of variation that will be evident among both the tsunami-hit ports and the substitute. 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. We assume that the effect diminishes with distance. However, the effect will increase with height of the wave that struck individual ports. Here we expect that the height of the weight is a measure of the destruction that took place and therefore the amount of exports that will be shifted from tsunami hit ports to other ports. We can only assume some functional forms on the exposure measure, rather than estimate it, but we can test the relevance by inspecting whether the exposure measure improves the inference of the coefficients relative to the model (12), which uses just an indicator function.

Using these measures we can augment model (12) to obtain

[14] Our model can be summarised in a standard panel framework,

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

The tsunami and substitution dummies are summarised in the column vector $x_{i,t}$, while $c_i$ represent individual $i$ (e.g. port×sector×month) unobserved time-constant effects. Therefore, $c_i$ can be estimated using only data from before 2011; $\bar{y}_i = c_i + v_i$, where $\bar{y}_i = \frac{1}{24}\sum_{t=\text{Jan 2009}}^{\text{Feb 2011}} y_{i,t}$, which excludes $x'$ since it contains no variation for the first 24 months in the sample. Subtracting, this equation from structural model, gives

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

where $\ddot{y}_{i,t} = y_{i,t} - \bar{y}_{i,t}$, 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 $c_i$. We believe that the close overlap between $x'_{i,t}$ and $c_i$ for the post-tsunami period makes it more appropriate to estimate $c_i$ using only the pre-tsunami data. We do present robustness result using the standard fixed effect estimator. Alternatively, one could estimate the equation using 1 year differences. This would not be ideal in our case since the effect we're 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 month effect of the year 2009 and 2011 such that the estimated parameters show a difference-in-difference effect relative to the the counter-factual ports.

$$\ddot{y}_{k,g,t} = \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{1,\tau} \text{I}(\text{hit}_{k,g,\tau}) \times \text{wave}_k + \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{2,\tau} \text{I}(\text{sub}_{k,g,\tau}) \times \text{exposure}_{k,g} + \epsilon_{k,g,t}. \quad (13)$$

The issue with the substitute ports is that there are potentially two effects working on them. The substitution part will only play a role if firms are located near a port that was hit, but the firm itself was not affected by the disaster. In case the firm itself was affected by the tsunami, total production will have decreased and there will be no substitution taking place. We showed above that the number of firms directly affected by the tsunami is likely to be a small percentage of the total. Nevertheless, we provide robustness result where we control for monthly industrial production at the prefecture level.

Finally, a note on the definition of group $g$. In line with the theory model we can also empirically distinguish all effects by sector if we group the export categories over defined sectors, $h$. However, the use of $g$ is more general than that, since we also have know the destination of each product category. So we can redefine $g$ to denote (groups of) destinations, $m$ rather than sectors. The method of estimation remains unchanged, but the demeaning process will always take the group level into account. We will present results on both below.[15] Additionally we can let the $\beta_1$'s and $\beta_2$'s be varying over the group rather than estimating one average effect. We will present results on that too.

## 3.2 Data

Monthly export statistics 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 was obtained from the Japanese Ministry of Trade website and is freely available. The values are represented as F.O.B. Customs are located both at sea and airports, we limit ourselves to seaports.[16] Road distances between ports were obtained from an route project based on OpenStreetMaps.[17]

Besides the export value (by sector and port) we calculate 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 $x$ for the export value, the

[15]The interaction of sector and destination is also possible in principle, but the 'bins' from which the margins would be calculated would become too small.

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

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

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. We will analyse our data with a single destination (the world), but both over a single and 2-digit sectors.

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.

## 3.3 Descriptive statistics

Table 4 presents some descriptive statistics for the variables of interest over various groups, but without distinction of sectors for brevity. The full period includes the entire sample period from 2009 to 2014. The pre- and post-periods present the data for Dec 2010 - Feb 2011, and Mar 2011 - Apr 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. Only for the trade share of tsunami-hit ports does the $t$-test indicate a significant drop in exports at the 5% level. What this means is mainly that the data series have a large variation and unconditional tests are not able to pick up the major shock, not even for the export value of the tsunami hit ports. This is interesting because it is clear that these ports were severely affected.

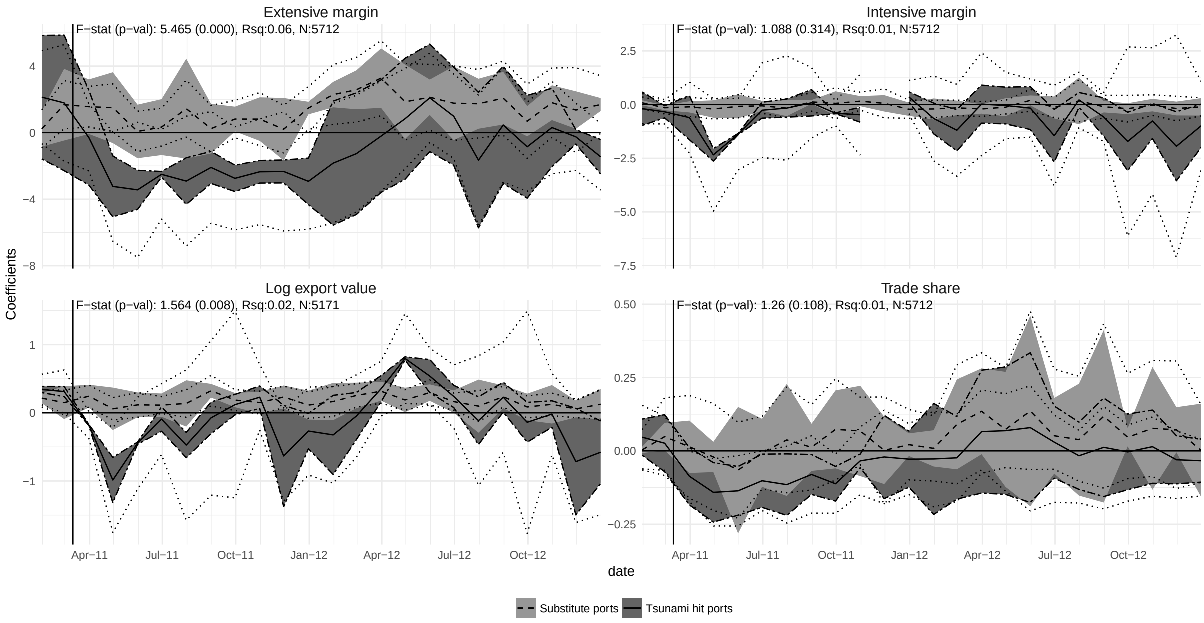
Density and distribution plots for the ports are presented in Appendix B.1. These plots are informative for the inspection that the tsunami-hit ports and substitution ports, although quite different in their characteristics, are not extraordinary relative to the entire collection of ports of Japan.

Table 4: Descriptive Statistics

| measure | group | n. ports | full mean | full sd | mean pre | sd pre | mean post | sd post | test |
|---|---|---|---|---|---|---|---|---|---|
| EM | Other | 77 | 12.57 | 16.95 | 12.14 | 17.08 | 12.79 | 17.11 | 0.68 |
| | Tsunami hit | 15 | 8.06 | 9.00 | 8.99 | 10.13 | 6.24 | 7.14 | 0.14 |
| | Substitute | 27 | 26.93 | 25.07 | 25.91 | 25.30 | 26.56 | 24.95 | 0.87 |
| | all | 119 | 15.26 | 19.51 | 14.87 | 19.55 | 15.09 | 19.46 | 0.88 |
| IM | Other | 77 | 3.85 | 6.87 | 3.58 | 4.62 | 4.30 | 8.17 | 0.25 |
| | Tsunami hit | 15 | 3.32 | 5.02 | 3.07 | 3.65 | 2.46 | 3.85 | 0.44 |
| | Substitute | 27 | 4.33 | 5.67 | 4.31 | 5.37 | 4.16 | 4.95 | 0.85 |
| | all | 119 | 3.89 | 6.41 | 3.69 | 4.69 | 4.03 | 7.13 | 0.44 |
| log(Value) | Other | 77 | 14.89 | 2.54 | 14.82 | 2.70 | 14.97 | 2.60 | 0.57 |
| | Tsunami hit | 15 | 14.67 | 2.20 | 14.77 | 2.04 | 14.39 | 1.89 | 0.39 |
| | Substitute | 27 | 16.50 | 2.23 | 16.47 | 2.13 | 16.47 | 2.21 | 0.99 |
| | all | 119 | 15.24 | 2.53 | 15.19 | 2.59 | 15.25 | 2.53 | 0.76 |
| n. var | Other | 77 | 407.69 | 792.10 | 408.31 | 799.54 | 407.74 | 797.70 | 0.99 |
| | Tsunami hit | 15 | 201.04 | 239.21 | 198.51 | 233.23 | 187.82 | 219.98 | 0.82 |
| | Substitute | 27 | 966.61 | 1278.90 | 944.27 | 1270.14 | 943.79 | 1264.12 | 1.00 |
| | all | 119 | 508.45 | 922.09 | 503.47 | 918.75 | 501.65 | 915.88 | 0.98 |
| TS | Other | 77 | 0.51 | 1.34 | 0.53 | 1.37 | 0.58 | 1.57 | 0.71 |
| | Tsunami hit | 15 | 0.19 | 0.25 | 0.22 | 0.28 | 0.11 | 0.16 | 0.03 |
| | Substitute | 27 | 2.14 | 4.34 | 2.08 | 4.36 | 1.99 | 4.15 | 0.89 |
| | all | 119 | 0.84 | 2.44 | 0.84 | 2.44 | 0.84 | 2.43 | 1.00 |

Statistics by group for extensive margin (EM), intensive margin (IM), log export value, number of product categories/varieties (n. var) and trade share (TS), calculated as defined in the text. ‘n. ports’ is the number of ports, ‘full mean’ and ‘full sd’ give the mean and standard deviation of the respective statistic over the entire sample period (2009-2014). The columns for ‘pre’ and ‘post’ indicate the same statistics based on the pre-tsunami and post-tsunami periods. The final column present the $p$-value of a simple t-test on the differences between the two periods for each statistic.

Figure 4: Overall margins of trade, 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 dotted lines represent a 95% confidence interval based heteroskedasticity-robust standard errors. 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.

## 3.4 Results

We estimate the above models on various export measures, namely, intensive margin (which includes the compositional margin), extensive margin, log(export value) and trade share. Each of these measures can be calculated over the defined groups. Since we recover 48 coefficients for each outcome variable (24 months for tsunami-hit and substitute ports) we present results of the coefficients graphically as a time plot. The relatively long time-span of analysis allows to observe a time patterns that would be difficult to discern when focusing only on the immediate aftermath of the tsunami. We provide confidence bands using both robust standard errors and clustered standard errors at the regional level. The 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.

### 3.4.1 Overall margins of trade

We will start doing our estimations based on the overall trade margins that make no distinction on sectors, effectively removing subscript $g$ from the estimation. In the next subsection we will reintroduce the groupings by sector and destination in order to gain further insights.

Figure 4 presents the first results based on model (12) and margins based on exports without sector definitions. On the horizontal axes time is indicated from January 2011 to December 2012. The vertical black line indicates the month of March 2011, the first month in which the data should show an effect from the tsunami. The horizontal zero-axis is accentuated to aid on the inspection on whether the two groups of ports exhibit a statistically significant different pattern from the counter-factual ports. In this way the plots allow for a range of comparisons, notably,

1. for each group (tsunami-hit ports and substitutes) relative to the counter factual at every point in time while having demeaned all observations with 2009-2010 data,
2. relative to the two months before the tsunami, and
3. relative to each other.

For the intensive margin of tsunami-hit ports, the coefficient of November 2011 is omitted as it was evidently outside of what could be expected indicating a point estimate of +9. Each plot represents one regression and some statistics regarding the model are indicated. The $F$-statistic is calculated as the difference between the estimated model and the projected variable with no additional regressors. The $F$-statistic and standard errors take a degrees of freedom adjustment for the projection/demeaning method.

While a time pattern appears 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. Confidence intervals at the 95% significance levels are indicated by the shaded areas for the clustered standard errors, while robust standard errors are indicated by the dotted lines (the shaded areas for the tsunami-hit coefficients is lined with a dashed pattern to aid inspections when the two area falls behind the shaded are of the substitution coefficients). 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. While the log export value appears to recover within a few months, it falls back again and remains relatively volatile, the extensive margin takes longer to recover and only at the start of 2012 become largely indistinguishable from zero and the substitute ports. The intensive margins shows overall much less variation than the extensive margin, with a similarly quick recovery. The trade share appears recovered by the start of 2012 in line with the mathematical relation between the three margins.

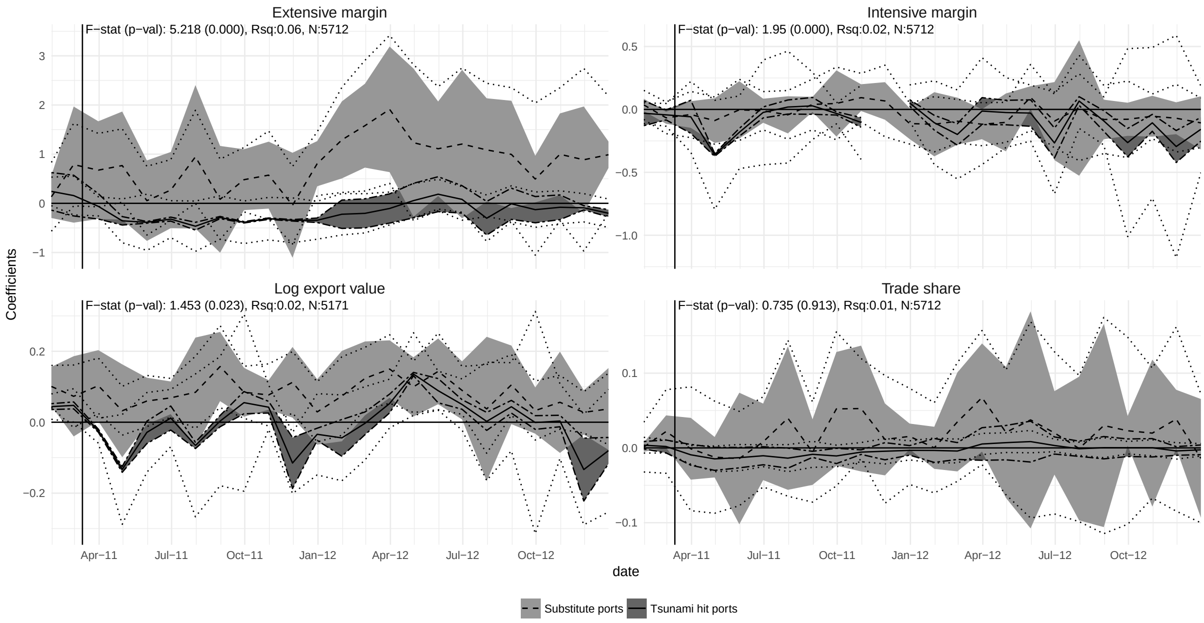
Focusing on the substitute ports we note that any response is much less dramatic relative to the fall of the tsunami-hit ports. This is not surprising overall. As was evident from the descriptive statistics there are more substitute ports and each of these are on average larger relative to the substitute ports. If there is any trade substitution the effect will be smaller than the shock from the destructed ports. 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. For the intensive margin the response is much smaller overall and largely indistinguishable from zero. For the log export value we find a significant increase from the summer of 2011 to the summer of 2012. Finally for the trade share, the point estimates suggest a sizeable and persistent bump for substitute ports, but the standard errors around the point estimates suggest a large variation within the group.

The 95% confidence interval of the clustered standard errors lies generally within the dotted lines of the robust standard errors. Since we know that the ports hit by the tsunami were dramatically affected, it appears that the robust standard errors are too conservative and the clustered standard errors are preferred for inference. Nevertheless, the difference between the two types of standard errors is minimal for the substitute ports. The pre-differencing method also works well to centre the coefficients around zero generally before March 2011. One can also observe here that using fixed effects for the entire time-period would likely make it harder to observe the persistent effect from the tsunami, which is something that we will inspect in the next section.

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 3 percentage points decline while there is a 2 percentage points increase for the substitutes at their respective peaks. Given the average extensive margin of 8.99 (see Table 4 second row, column 'mean pre') for the tsunami-hit ports this means 33% ($= -3/8.99 \times 100$) decline. For the substitute ports the effect is smaller, presenting about a 8% ($=2/25.9 \times 100$) 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, suggesting massive drop of exports from these ports for the first few months after the distaster, equivalent to 63% ($= \left(e^{\beta} - 1\right) \times 100$) decline which is otherwise not surprising. What is interesting is the relatively quick recovery, while the substitute ports on average at their peaks in August 2011 would have gained around 35% ($= (e^{0.30} - 1) \times 100$) in additional exports. However, the confidence bands are rather wide suggesting that there was a wide variation of experiences among the different ports.

From this first set of results we can gain further insights by varying our analysis over various direction. Firstly we will show model (13) using the same margins. Results are presented in Figure 5. 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),

Figure 5: 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 4

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 majorly affected. 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.

In Table 5 we present variations of our setup using a single statistic for the hit and substitute ports for brevity. The coefficients of the first 12 months after March 2011 are summed, and the standard error of this sum is calculated using the delta method. One can interpret this statistic as the cumulative gain or loss from the tsunami over these 12 months. The first few lines give the coefficient with the robust and by-region-clustered standard errors as presented in the figures before for the purpose of providing a baseline against which to evaluate variations on our main specification.

We present the coefficients were standard errors are clustered by port followed by a specification which uses fixed effects rather than a pre-differenced variables. In this case the cumulative coefficients for the hit ports is no longer statistically significant at conventional levels, while for the substitute ports it is little changed relative to the clustering at the regional levels. Because we believe that a sensible variance estimator should confidently reject the hypotheses that tsunami hit ports were not affected by the tsunami we prefer the regional-clustered variance estimator.

It is also encouraging to see that the use of a more common fixed effects estimator

Table 5: Summary robustness results

| Model | | Stat | EM | IM | lValue | TS |
|---|---|---|---|---|---|---|
| Benchmark | hit | $\sum\beta$ | −25.324 | 0.422 | −2.266 | −0.838 |
| | | rse | 5.590*** | 12.725 | 1.355* | 0.204*** |
| | | cse | 12.240** | 2.115 | 0.849*** | 0.089*** |
| | sub | $\sum\beta$ | 19.242 | 0.153 | 3.482 | 0.560 |
| | | rse | 2.943*** | 1.073 | 0.437*** | 0.362 |
| | | cse | 7.643** | 0.881 | 1.755** | 0.252** |
| + cluster at port instead of region | hit | cse | 17.685 | 17.425 | 3.543 | 0.587 |
| | sub | cse | 6.844*** | 2.693 | 1.100*** | 0.910 |
| + fixed effects instead of pre-differencing | hit | $\sum\beta$ | −27.493 | 5.093 | −2.249 | −0.700 |
| | | cse | 15.940* | 15.605 | 3.203 | 0.551 |
| | sub | $\sum\beta$ | 16.487 | 4.993 | 3.567 | 0.686 |
| | | cse | 6.564** | 3.955 | 1.282*** | 0.855 |
| + add prefecture production as control | hit | $\sum\beta$ | −11.343 | −1.089 | −0.580 | −0.470 |
| | | cse | 5.972* | 5.048 | 1.207 | 0.247* |
| | sub | $\sum\beta$ | 18.374 | 2.526 | 2.995 | 0.281 |
| | | cse | 5.144*** | 2.352 | 1.182** | 0.546 |
| Exposure | hit | $\sum\beta$ | −3.396 | 0.711 | −0.322 | −0.094 |
| | | rse | 0.714*** | 2.309 | 0.271 | 0.026*** |
| | | cse | 0.809*** | 0.328** | 0.043*** | 0.010*** |
| | sub | $\sum\beta$ | 109.185 | 0.032 | 28.371 | 3.122 |
| | | rse | 17.775*** | 4.717 | 6.338*** | 1.568** |
| | | cse | 44.164** | 3.218 | 21.668 | 1.429** |
| + cluster at port instead of region | hit | cse | 2.322 | 3.102 | 0.712 | 0.080 |
| | sub | cse | 38.105*** | 10.904 | 14.470** | 3.498 |

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 for Benchmark and Exposure models is at the regional level. $p < 0.01$ ***, $p < 0.05$ **, $p < 0.1$ *

gives completely consistent results. The estimation used here can be represented as

$$y_{k,h,t} = \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{1,\tau}\mathrm{I}(\text{hit}_k) + \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{2,\tau}\mathrm{I}(\text{sub}_k) + \alpha_{k,h} + \theta_{\text{month}} + \theta_{\text{year}} + \epsilon_{k,h,t}, \quad (12')$$

$$k = 1, \ldots, 119;\ h = 1,\ t = \text{jan 2009},\ldots,\text{Dec 2015}. \quad (14)$$

Notice that the dependent variables have changed to non-transformed measures, while the fixed effects are introduced for the port-sector, month and year level. While models (12) and (13) are in fact using an interaction method of port-sector and month, in this case we include them additively.

The next model adds two additional covariates to our model, $\log(production_{k,t})$ and $\log(\sum_{l=-k} production_{l,t})$. The variable $production_{k,t}$ is monthly aggregate industrial production at the prefecture level, which we match to each port.[18] The second covariate is

[18]Data from the Japanese Ministry of Industry.

meant to captures the effect from declining production in the surrounding regions through the sum of production for the surrounding prefectures.[19] Although we argued that firms were affected to a very limited extend, if this were not the case and the surrounding regional production was indeed affected by the earthquake our substitution effect might be biased towards zero. We take the log of of both variable and pre-difference as before. The results are little changed, in particular for the substitution effect, suggesting that the substitution effect is really due to the state of the ports rather than the activity of firms. We perform similar variation for the estimation of (13), called exposure. Again, in the majority of these variations the results are not altered. In some variations the standard errors are so wide that not even for the tsunami hit ports the effect is not statistically significant at the 10% level or higher, which is a helpful indicator to judge whether the estimation method for the coefficient and the standard error is appropriate. Plots for some of these regressions are presented in Appendix B.3.

### 3.4.2 Sector margins of trade

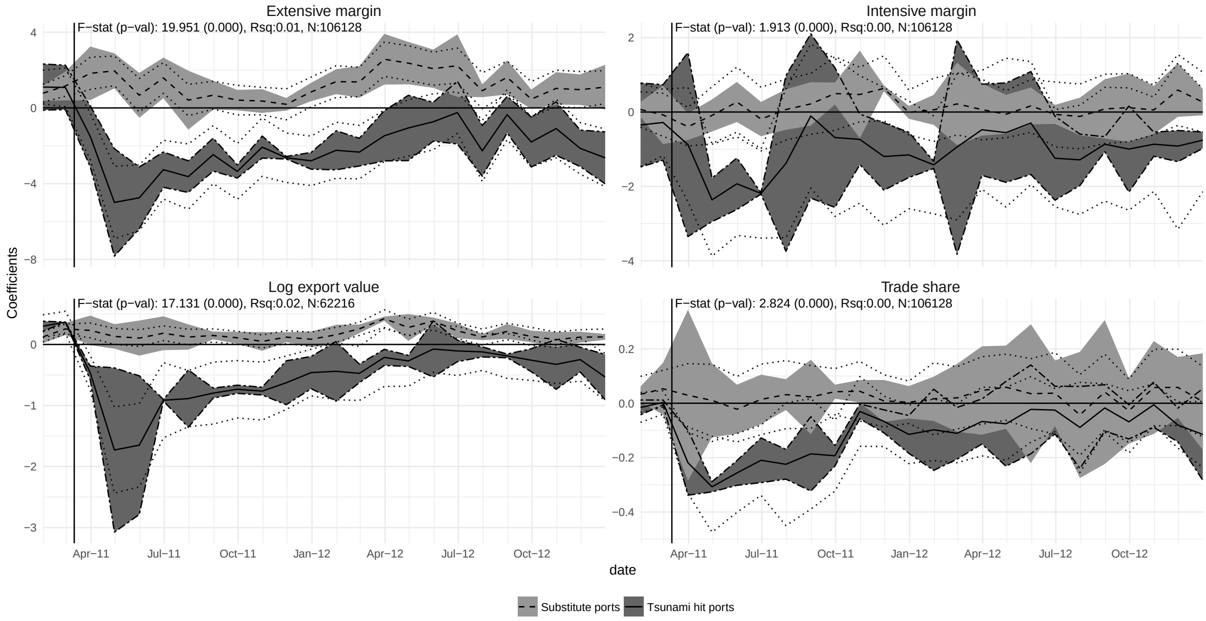
We next turn to the analysis at the level of sectors, $h$, the definitions of which are derived from the first two digits of their HS code, details of which are given in Appendix B.4. This matches the theoretical model where we allowed for sector specific effects on the margins of trade. An additional econometric benefit here is that the outcome variables are demeaned at the sectoral level. At the same time we can keep track of the sectors in which the tsunami-hit ports were exporting in 2010, rather than defining this at the product level. Given this additional level of detail the estimates should be more precisely estimated. Importantly, for substitute ports we can now additionally control for the difference between sectors that were hit by tsunami and those that were not. For instance, for a certain substitute port, one sector my be 'treated' since a tsunami-hit port was exporting in the same sector, but another may not be treated and therefore belongs to the group of counterfactuals. Note that we greatly increase the number of observations in this way as every port is now represented through a double digit number of sectors. In this case the cluster procedure becomes even more relevant, but clustering at the regional level is still appropriate as it nests clustering at the port level.

The plots in Figure 6 indicate that the sectoral perspective does help to gain efficiency in the estimation. While the patterns are generally similar, the precision of the estimates is better and the month-to-month volatility of the coefficients has decreased, while the amplitude of the regressors has generally increased. From these plots it is now also clearer that shock has a similarly persistent effect for the log of the export value as it has for

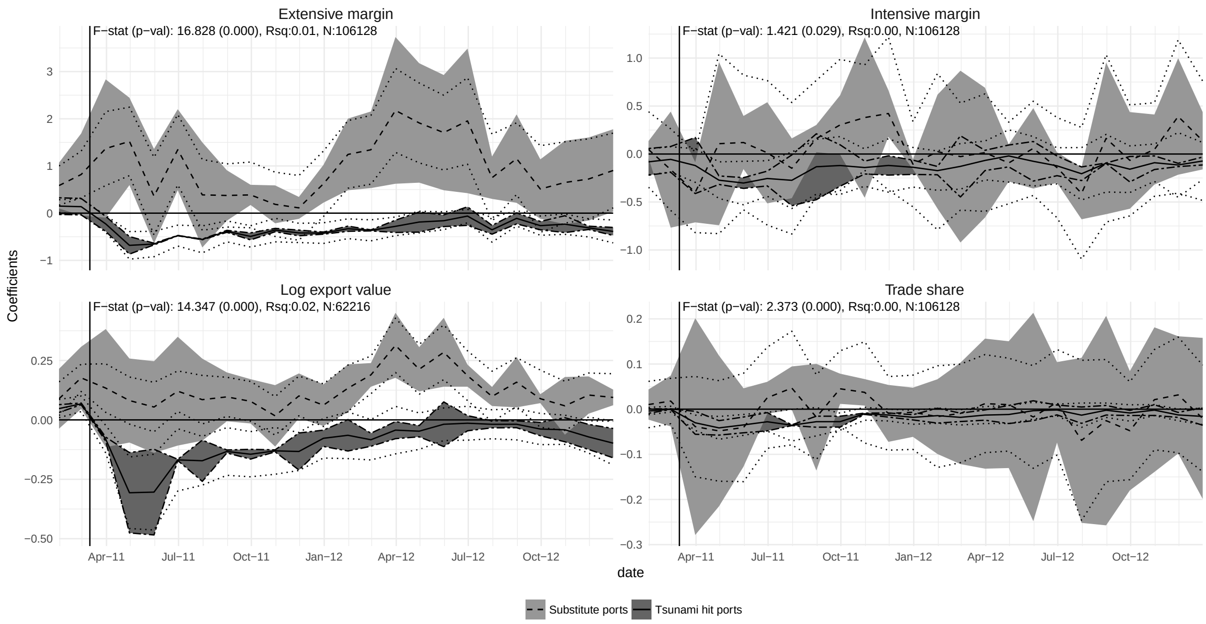
[19]To be precise, the 'surrounding prefectures' for certain prefecture is defined based on the treatment area. For prefectures in Tohoku, Kanto, Hokoriku and Tokai it is the sum of all prefectures in this area, for prefectures outside of those four regions the surrounding prefectures are the sum of all except in those four.

Figure 6: Sector margins of trade

(a) model (12)




(b) model (13)




See notes of Figure 4

the extensive margin. While for tsunami-hit ports the estimated effect on the intensive margin and the trade share appears to have decreased, for substitute ports the estimates suggest that the average effect is around zero. Model (13) helps to increase the precision of the coefficients on all measures for the tsunami-hit ports but it does not do so for the substitute ports. Specifically for the effect on log export value it rescales the effect making it evident that there is a significant bump from the start of 2012 that coincides with a recovery of the tsunami-hit ports, and the pattern is similar to the one observed for the extensive margin.

The combination of these results all point to effects that are in line with the theoretical model. The tsunami-hit ports observe a significant decline in exports, that this can be decomposed in to a extensive margin and intensive-compositional margin, where the major part of the effect goes through the former rather than the latter. For the substitute ports we are able to observe the opposite effect, but the effect is less precisely estimated. For the substitute ports therefore the effect is evident in the log export value and extensive margin rather than in the intensive margin or trade share. Moreover, the substitution effect appears stronger during the recovery face rather than as an immediate response to the disaster.

Next we allow the effect of each sector to be estimated independently (as if our $\beta$ are subscripted by $h$). Rather than presenting this graphically we calculated again the sum over the 12 month period from March 2011 onwards. Table 6 presents results where the each row represent a separate regression. The results are ordered descending by the extensive margin. What we find is that fresh unprocessed/fresh products and high-tech products have the largest substitution effect. On the other extreme we find bulk industry goods. As suggested by Todo et al. (2015), the supply chain may be critical here for the technology goods that are included in the categories of the second to fifth 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 least substituted. This intuitive relation between product characteristics substitution supports findings in the before mentioned studies that supply chains are important for the understanding of trade dynamics.

## 3.5 Margins by destination

As a final exploration we look at the effects by destination regions (similarly as before, as if our $\beta$ are subscripted by $m$ for destinations).[20] Again we present the results in a table with the sum over the first 12 months from March 2011, see Table 7.

[20]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

| | | EM | | lValue | |
|---|---|---|---|---|---|
| Name | stat | hit | sub | hit | sub |
| unprocessed fish and other sea animals and plants | $\sum\beta$ | −123.749*** | 56.621** | −3.72*** | 3.165 |
| | cse | 32.905 | 25.979 | 0.613 | 7.719 |
| Optical and photographic | $\sum\beta$ | 2.944 | 54.904*** | −2.36 | 10.047 |
| | cse | 4.313 | 10.019 | 4.385 | 10.355 |
| Electrical machinery and appliances | $\sum\beta$ | −42.975*** | 35.125*** | −1.481 | 0.642 |
| | cse | 14.407 | 10.225 | 1.717 | 3.016 |
| Machinery and mechanical appliances | $\sum\beta$ | −34.287** | 34.699*** | 2.553* | 7.282 |
| | cse | 15.802 | 11.433 | 1.354 | 6.747 |
| Plastics | $\sum\beta$ | −48.964*** | 28.166*** | −7.954** | 1.887*** |
| | cse | 15.777 | 10.289 | 3.549 | 0.238 |
| Chemical products | $\sum\beta$ | −46.475*** | 17.416*** | −9.645*** | 1.62 |
| | cse | 14.952 | 1.124 | 0.076 | 2.384 |
| Other vehicles | $\sum\beta$ | −12.743 | 16.852 | −4.899 | 6.44 |
| | cse | 43.495 | 28.049 | 6.931 | 4.099 |
| Other metals and articles thereof | $\sum\beta$ | −59.153*** | 9.99 | −9.844*** | 2.205** |
| | cse | 20.406 | 6.161 | 3.792 | 0.896 |
| Articles of iron and steel | $\sum\beta$ | −11.425*** | 9.584 | 1.627 | 5.281*** |
| | cse | 2.452 | 5.988 | 2.9 | 1.89 |
| Processed agricultural products | $\sum\beta$ | −34.66*** | 7.794 | −4.961*** | 0.206 |
| | cse | 6.142 | 17.79 | 1.171 | 1.767 |
| Paper and printed | $\sum\beta$ | −59.28*** | 5.403 | −10.348*** | 0.445 |
| | cse | 15.727 | 16.499 | 0.284 | 2.321 |
| Other organic based products | $\sum\beta$ | −58.224*** | 4.711** | −1.73 | 4.074*** |
| | cse | 21.01 | 2.087 | 1.396 | 0.412 |
| Intermediate textiles | $\sum\beta$ | 1.261** | 4.417 | −7.902*** | 8.276 |
| | cse | 0.564 | 12.703 | 1.072 | 5.831 |
| Iron and steel | $\sum\beta$ | −22.99*** | −19.164*** | −3.997** | 1.168 |
| | cse | 4.691 | 5.547 | 1.964 | 2.094 |

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 $\exp(\beta) - 1$.

Table 7: Differentiated effects over destination regions

| Region | Stat | EM Hit | EM Sub | lValue Hit | lValue Sub |
|---|---|---|---|---|---|
| Middle and South America | $\sum\beta$ | $-27.714^{***}$ | $25.450^{***}$ | $-2.092$ | $1.730^{***}$ |
| | rse | 7.687 | 6.818 | 1.570 | 0.351 |
| Asia | $\sum\beta$ | $-25.397^{***}$ | $12.236^{***}$ | $-2.358^{*}$ | $2.380^{***}$ |
| | rse | 4.691 | 1.934 | 1.216 | 0.333 |
| North America | $\sum\beta$ | $-6.049$ | $11.804^{***}$ | $-3.884^{***}$ | $2.310^{***}$ |
| | rse | 5.269 | 4.470 | 1.183 | 0.357 |
| Western Europe | $\sum\beta$ | $-21.332^{***}$ | $8.475^{***}$ | $-1.630$ | $2.412^{***}$ |
| | rse | 4.437 | 2.810 | 1.458 | 0.362 |
| Middle East | $\sum\beta$ | $-0.644$ | 5.730 | $-1.944$ | $2.227^{***}$ |
| | rse | 5.579 | 5.862 | 1.575 | 0.306 |
| Oceania | $\sum\beta$ | $-19.266^{***}$ | 4.837 | $-4.028^{***}$ | $1.996^{***}$ |
| | rse | 4.540 | 4.320 | 1.222 | 0.367 |
| Africa | $\sum\beta$ | $-41.128^{***}$ | 0.304 | $-2.778^{**}$ | $2.687^{***}$ |
| | rse | 6.743 | 5.123 | 1.407 | 0.388 |
| Central and East Europe, incl. Russia | $\sum\beta$ | $-44.109^{***}$ | $-2.389$ | $-2.949^{**}$ | $2.039^{***}$ |
| | rse | 8.006 | 4.615 | 1.423 | 0.361 |

Statistics are the sum of the first twelve months from March 2011 onwards. Robust standard errors are calculated using the delta method. For the log export value, coefficients were transformed using $\exp(\beta) - 1$.

The results indicate that the substitution effect is the biggest for all Americas, Western Europe and and Asia. Instead of trade distance, market size seems to be the relevant driver of the size of the substitution effect given that these three regions represent Japan's biggest export markets. The other regions have both smaller coefficients which are statistically not different from zero at the usual significance levels.

## 3.6 Robustness

In the appendix we present further robustness results. None of these alter the conclusions we can draw from the main results. We estimated the effect for each of the four Japanese treatment regions separately (see Appendix B.3, Figure B-4). 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.

We vary the distance at which ports are assumed to be exposed to treatment (Appendix Figure B-5). This variation matters for the size of the estimated coefficients but the general pattern is similar to what we have shown so far. We add Hokkaido ports as treated (both hit and substitute) as indicated at the map of Figure 3 (Appendix Figure B-6, a-b). Although the general pattern remains, the standard errors become much bigger, indicating that the ports of Hokkaido were not similarly affected as those in Kanto and Tohoku. Another way to show that the ports thus far designated as substitute were indeed affected as such is by running a placebo analysis (Appendix Figure B-6c). While excluding our original substitute ports we random select 10 ports from our previous counterfactuals to serve as substitute ports. There should be no statistically significant effect estimated. This is indeed what we find.

Finally, we handle the treated sectors at the port level differently. Whereas in Figure 6a we treated sectors as treated or not for a certain port (given that the port was in one of the four regions around the tsunami-hit area), in Appendix Figure B-6d we indicate treatment at the port level rather than the sector. This variation gives practically identical results relative to those presented in Figure 6a.

# 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. Multiple ports are in action 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 both forms of internal trade costs. We analytically present comparative statistics results for each margin of trade and show export switching from one port to the another can be accounted for exogenous variation in both port specific local transportation costs and port specific fixed export costs. Finally, we test the prediction of the model with Japanese custom 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.

Therefore, the implication of this paper 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 a international supply chain might switch between ports but would not affect aggregate export volumes.

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# A 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 $k > s$,

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

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

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

Thus when $f_{ijs}/f_{ijk}>\left(\mu_{ijs}/\mu_{ijk}\right)^{1-\sigma}$, 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,

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

From (3) and (2), we can express profits in exporting from port $k$ as

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

The similar expression holds for port $s$. Deriving these expressions with respect to $\varphi^{\sigma-1}$ for each port, we have $\left(\mu_{ijk}/\mu_{ijs}\right)^{\sigma-1}>1$ so that (A-1) holds. On the other hand, when $\left(\mu_{ijk}/\mu_{ijs}\right)^{\sigma-1}<1$, 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 $\varphi$ eventually chooses to export from one specific port $k^*$ that maximizes its exporting profits $d_{ijk^*}\left(\varphi\right)$, specifically by solving the following problem.

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

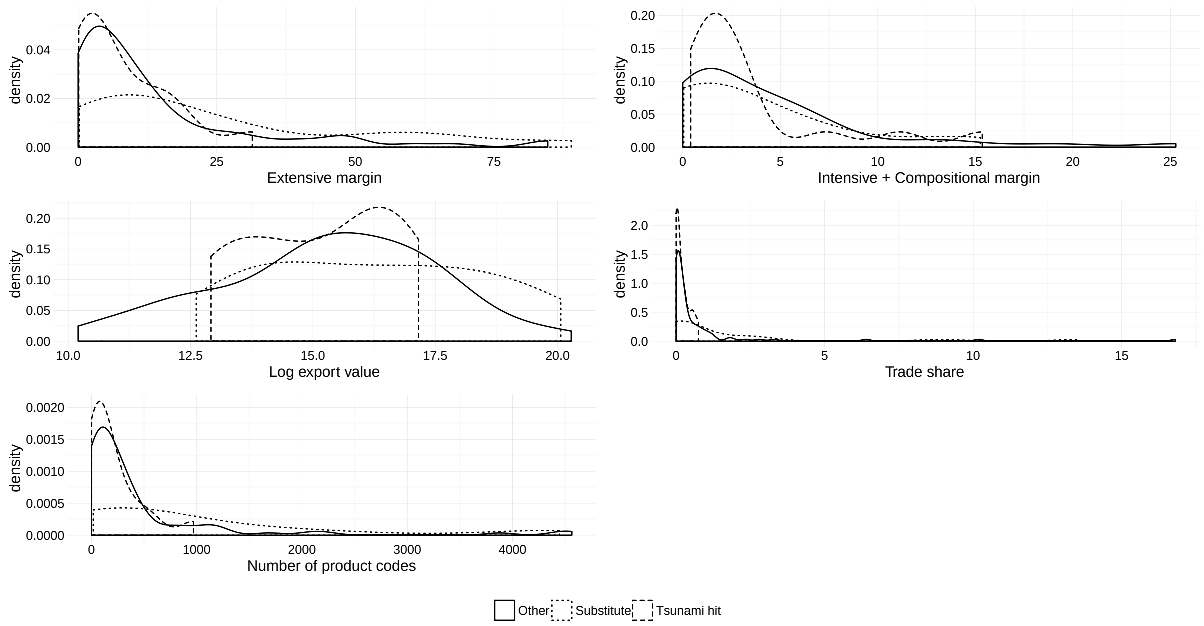
Together with the specific preference of firms with respect to exporting port as defined previously, the above condition establishes the proposition 1.

# B Additional empirical results

## B.1 Additional statistics on ports

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

Figure B-1: Density plot - port level




margins or values over 2009-2010 (i.e. pre-tsunami). 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 centred relative to the other ports.

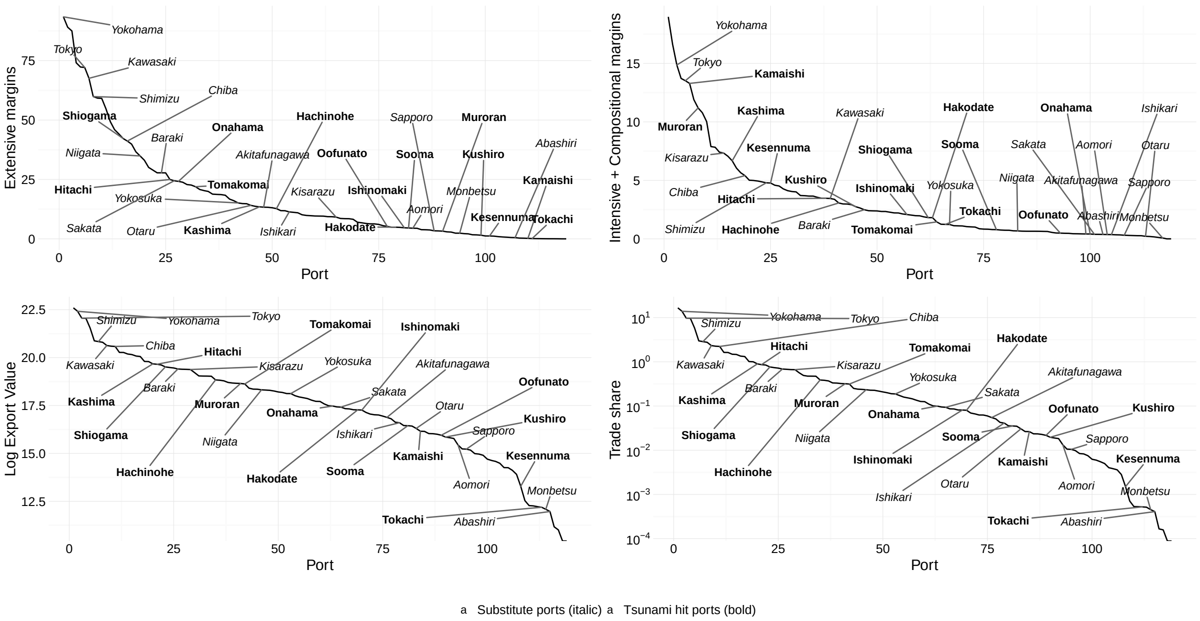
## B.2 Direct flood impact

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.

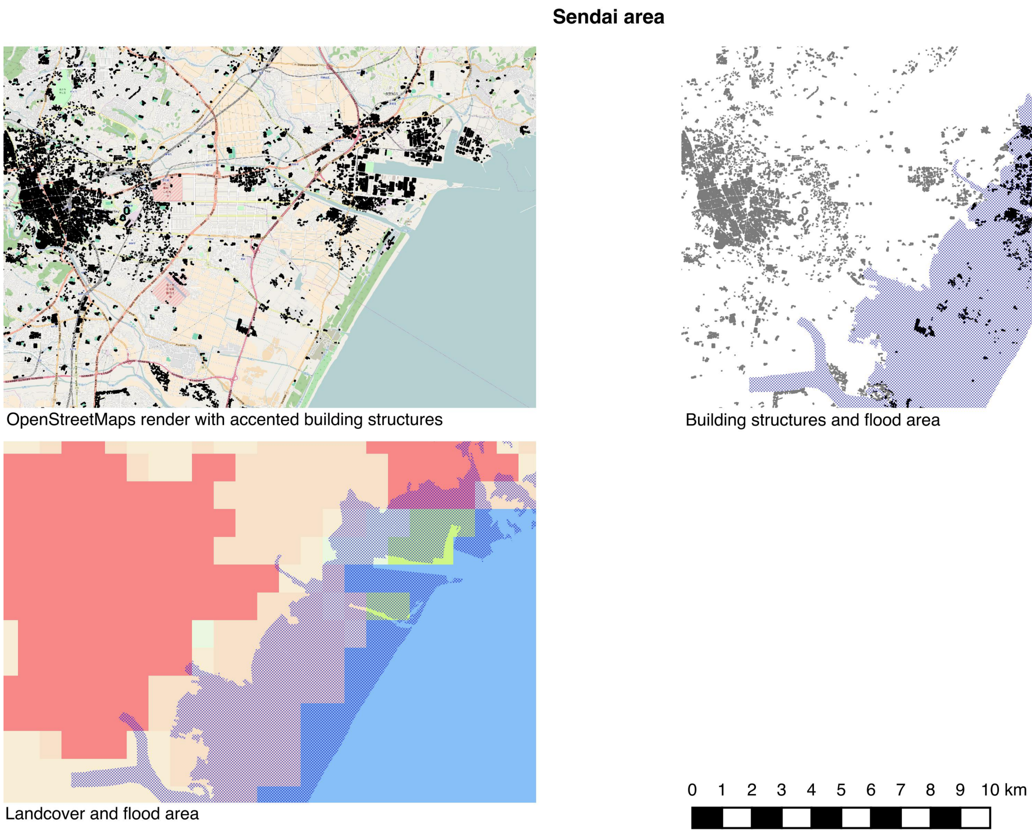
We obtained a shape files of the flooded region from Geospatial Information Authority of Japan (GSI Japan, part of the Ministry of Land, Infrastructure, Tourism and Transport), which contains a number of polygons that indicate the maximum flood extend. These were created using arial images during the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

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




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



sible 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 centres, 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.

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.

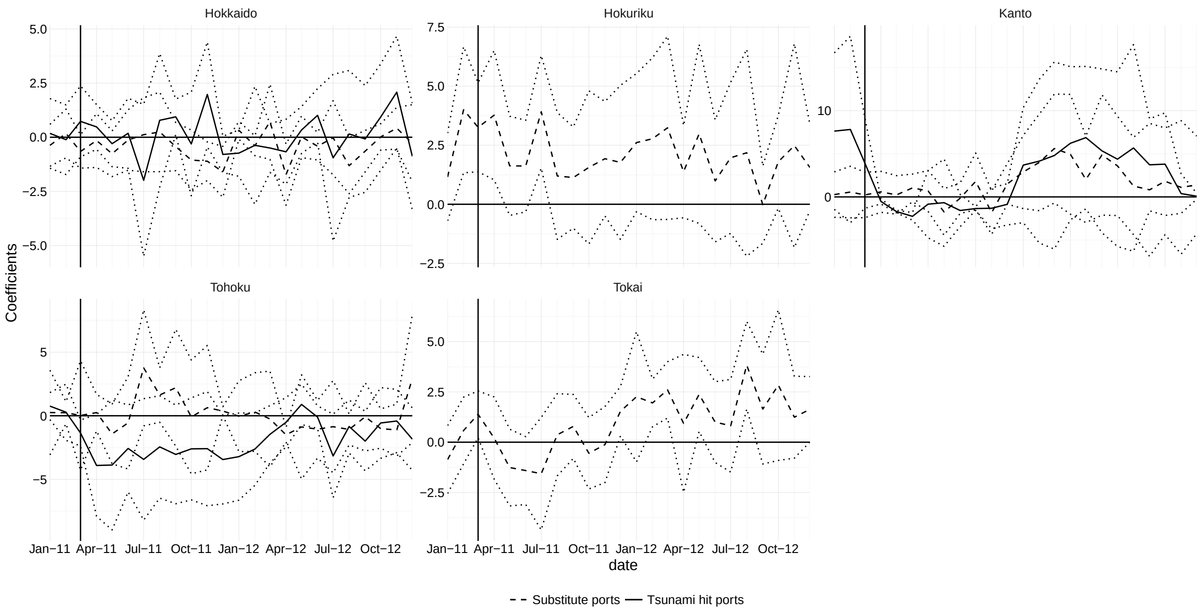
## B.3 Additional regression results

## B.4 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-1.

Figure B-4: results by region, Overall margins, model (12)

(a) Extensive margins




(b) Log Export value

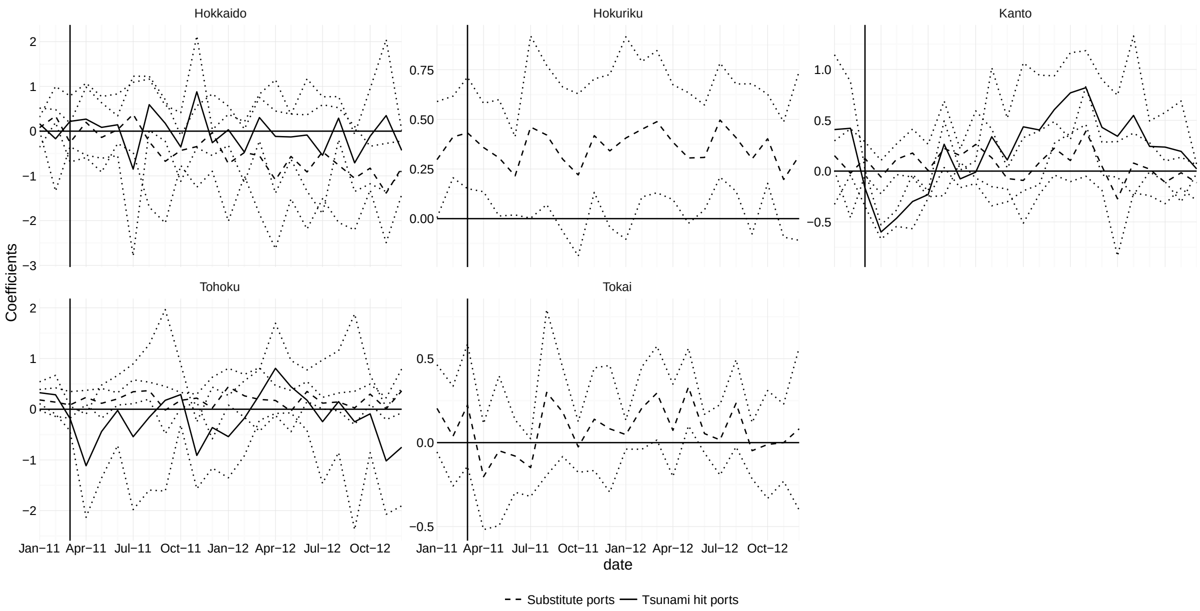
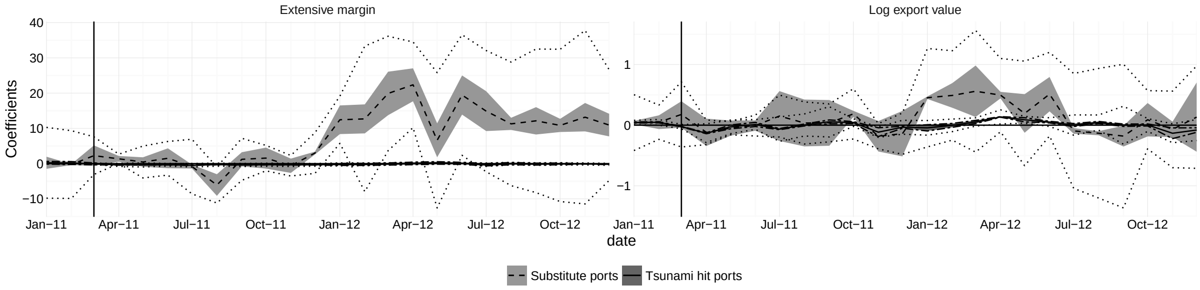
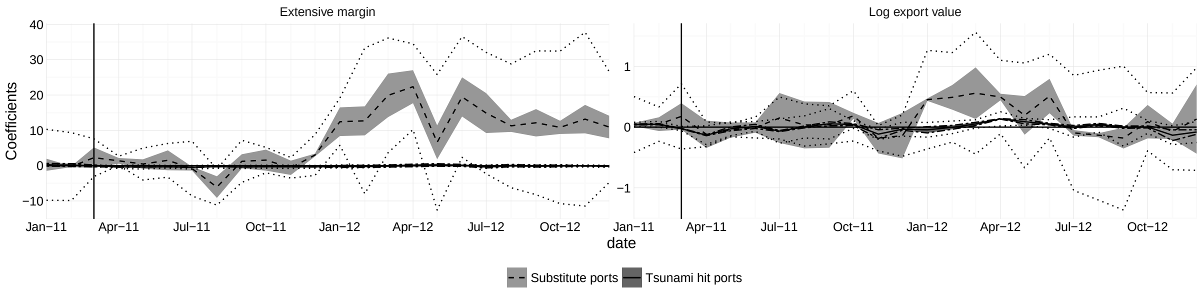


Figure B-5: Robustness analysis - substitute port distance, model (13)

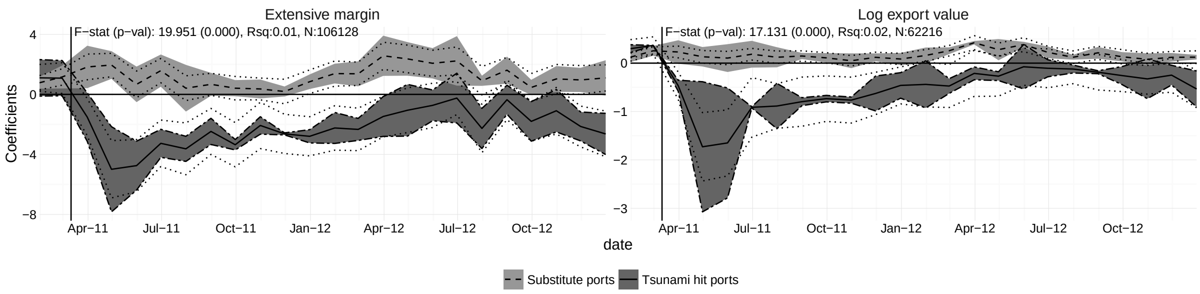
(a) Overall margins, exposure capped at 100km




(b) Overall margins, exposure capped at 500km




(c) 2d sectors, exposure capped at 100km




(d) 2d sectors, exposure capped at 500km

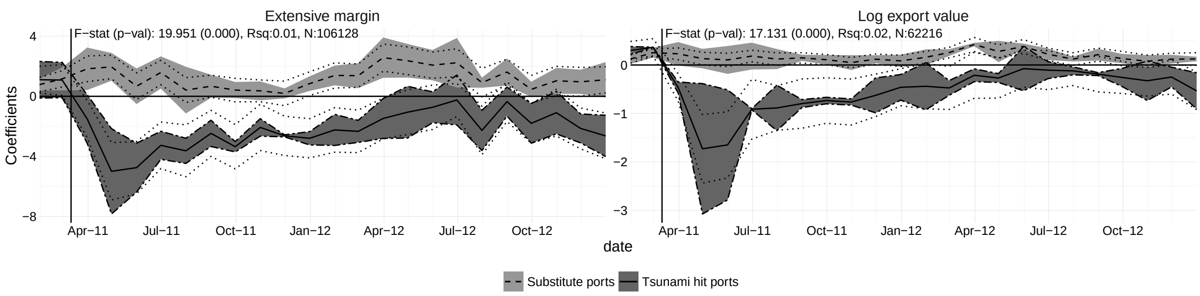
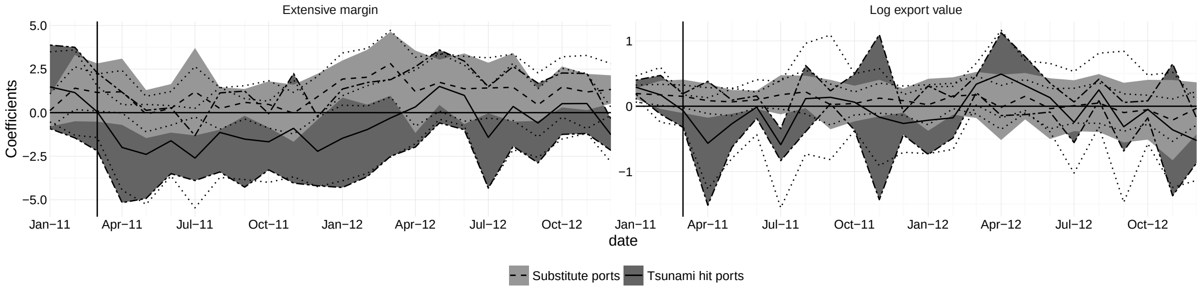
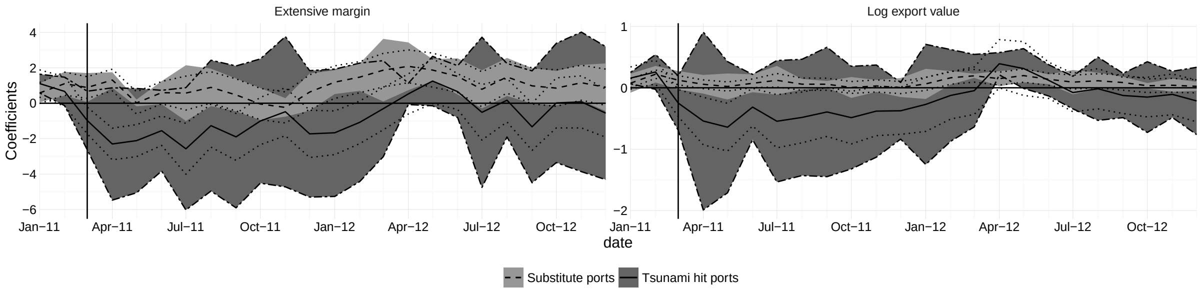


Figure B-6: Robustness analysis - substitute port selection

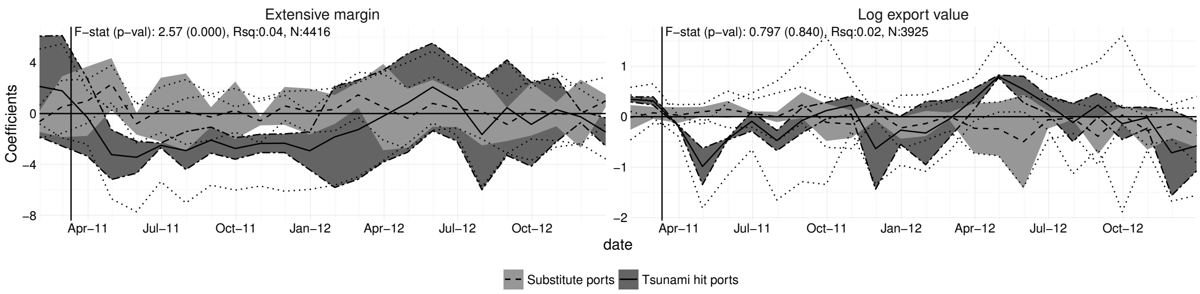
(a) Overall margins, model (12), with Hokkaido as treated




(b) sector margins, model (12), with Hokkaido as treated




(c) Overall margins, model (12), placebo analysis




From the original counterfactuals, ten ports were randomly designated 'substitute', the original substitute ports were excluded from the dataset, and the tsunami hit port left unchanged. The cumulative effects (with clustered standard errors in brackets) are: $\sum \beta_{\text{sub}}^{EM} = 5.00\,(3.56)$, $\sum \beta_{\text{sub}}^{lValue} = 0.25\,(0.68)$.

(d) sector margins, model (12), substitute treatment at port level

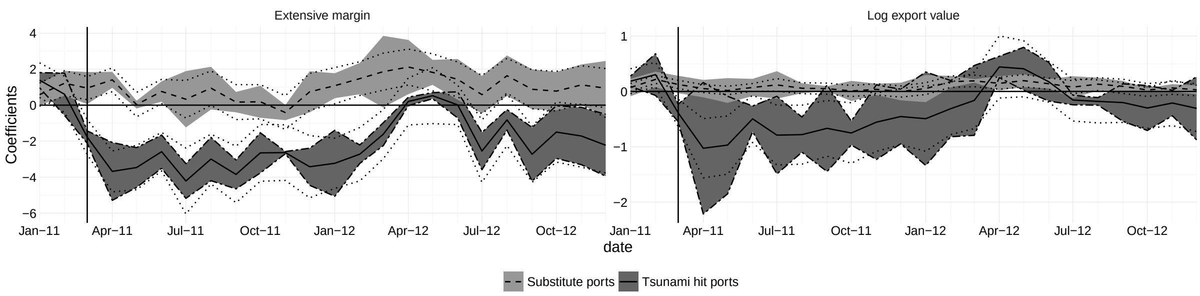
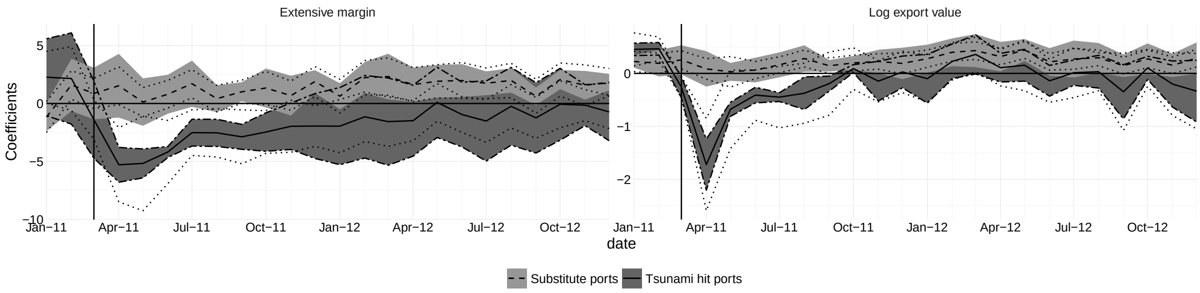
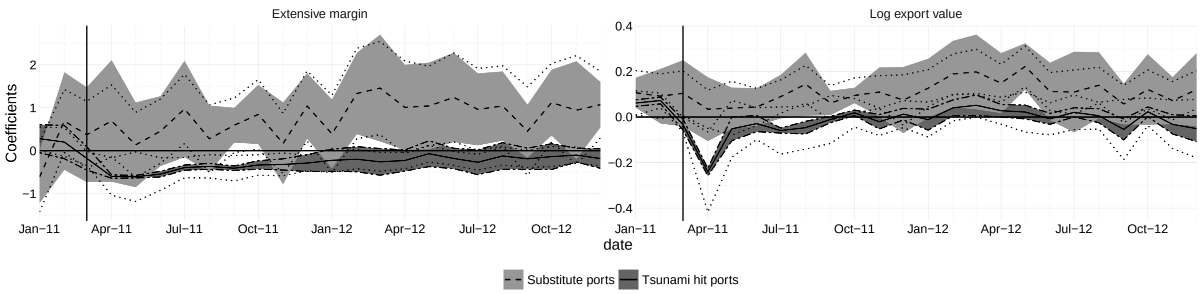


Figure B-7: Robustness analysis - Fixed Effects models

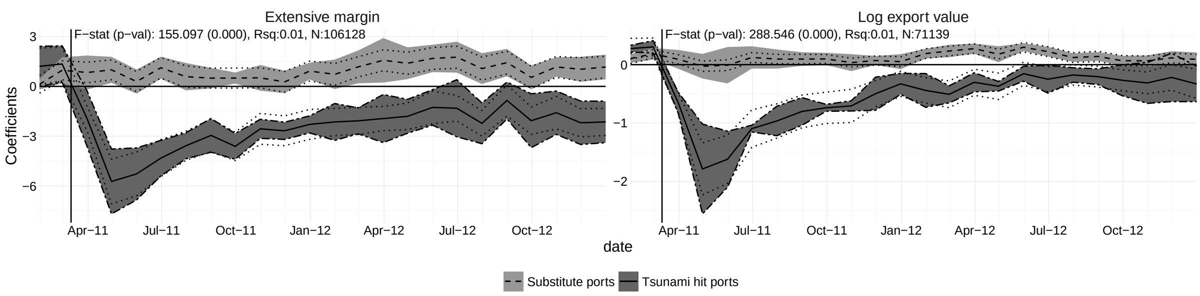
(a) Overall margins, model (12) with fixed effects



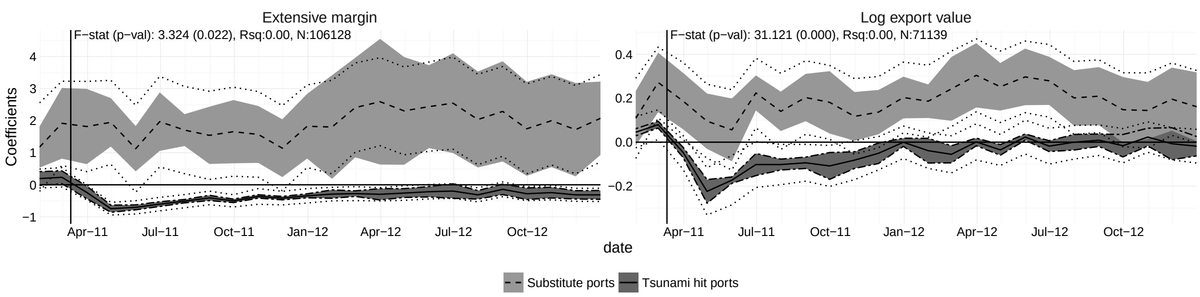

(b) Overall margins - model (13), with fixed effects




(c) 2d sectors, model (12) with fixed effects




(d) 2d sectors, model (13), with fixed effects




The fixed effects model used here can be represented as

$$y_{k,h,t} = \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{1,\tau} \mathrm{I}(\text{hit}_k) + \sum_{\tau=\text{Jan 2011}}^{\text{Dec 2012}} \beta_{2,\tau} \mathrm{I}(\text{sub}_k) + \alpha_{k,h} + \theta_{\text{month}} + \theta_{\text{year}} + \epsilon_{k,h,t}, \quad (12')$$

$$k = 1, \ldots, 119;\ h = 1,\ t = \text{jan 2009}, \ldots, \text{Dec 2015}.$$

Note that we use fixed effects for the port-sector level, month and year additively. See further the discussion in the main text around (14) on p. 29. For model (13) we do the same.

Table B-1: 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 animals and plants | 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 | | |
| 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 |

Table B-1: Sector definitions, *continued*

| HS code | HS name | n var | new sector | new n.var |
|---|---|---|---|---|
| 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 | | |