

Input Linkages and the Transmission of Shocks: Firm-Level Evidence from the 2011 Tōhoku Earthquake*

Christoph E. Boehm
U.T. Austin

Aaron Flaaen
Federal Reserve Board
of Governors

Nitya Pandalai-Nayar
U.T. Austin

December 13, 2017

First version: October 2014

Abstract

Using novel firm-level microdata and leveraging a natural experiment, this paper provides causal evidence for the role of trade and multinational firms in the cross-country transmission of shocks. The scope for trade linkages to generate cross-country spillovers depends on the elasticity of substitution with respect to domestic inputs. Using the 2011 Tōhoku earthquake as an exogenous shock, we structurally estimate production elasticities at the firm-level and find greater complementarities in input usage than previously thought. For Japanese affiliates in the U.S., output falls roughly one-for-one with declines in imports, consistent with a relationship between imported and domestic inputs that is close to Leontief.

JEL Codes: E32, F44, F23, F14

Keywords: Multinational Firms, International Business Cycles, Elasticity of Substitution

**Boehm*: chris.e.boehm@gmail.com, *Flaaen*: aaron.b.flaaen@frb.gov, *Pandalai-Nayar*: npnayar@utexas.edu. We would like to thank Andrei Levchenko, Kyle Handley, Matthew Shapiro, and Linda Tesar for valuable comments, suggestions, and support. We also thank our discussants Rob Johnson, Eduardo Morales, Joan Monras, Sebnem Kalemlil-Ozcan, and Teresa Fort as well as seminar participants at the IMF, Michigan, Stanford, FRB, Colorado, Washington, BU, Dallas Fed, FREIT-EITI, Barcelona GSE-SI, NBER SI-ITM, SED, FREIT -RMET and Johns Hopkins-SAIS for helpful comments and suggestions. We particularly thank Phil Luck for sharing his code. This research has received research grants from the Michigan Institute for Teaching and Research in Economics (MITRE), for which we are very thankful. Support for this research at the Michigan RDC from NSF (ITR-0427889) is also gratefully acknowledged. Any opinions and conclusions expressed herein are those of the authors and do not necessarily represent the views of the U.S. Census Bureau, the Board of Governors, or its research staff. All results have been reviewed to ensure no confidential information is disclosed.

1 Introduction

A well-established fact in international economics is that countries with greater bilateral trade display greater business cycle synchronization (Frankel and Rose, 1998). Yet, whether such comovement arises due to common shocks or due to endogenous spillovers, or both, remains the subject of much discussion (Imbs, 2004; Burstein, Kurz, and Tesar, 2008; di Giovanni and Levchenko, 2010; Johnson, 2014). Isolating specific mechanisms through which trade and foreign direct investment induces spillovers has proven challenging. Due to the multitude of linkages between advanced economies, studying any specific mechanism is complicated by a host of confounding factors. There rarely is exogenous variation to identify individual spillover channels.

This paper provides empirical evidence for the cross-country transmission of shocks via inelastic production linkages, primarily of multinational firms. The principal mechanism at work is not new; the idea that input-output linkages are a key channel through which shocks propagate through the economy dates back to at least Leontief (1936) or Hirschmann (1958). Two advances in this paper permit a new evaluation of the nature and quantitative importance of these linkages. First, we utilize the March 2011 Tōhoku earthquake and tsunami as a natural experiment of a large and exogenous shock, disrupting production in Japan and spilling over to the United States. Second, we build a novel dataset that, for the first time, links restricted U.S. Census Bureau microdata to firms' international ownership structure. This information permits a forensic focus on those firms affected by the shock, thereby allowing us to study the technological underpinnings governing its international transmission. Our main finding is that the short-run elasticity of substitution between different inputs is near zero.

As disruptions to imports of final goods would be unlikely to affect the importer's production, we begin by developing a new methodology for classifying firm-level imports as intermediates or final goods. We document that foreign multinationals rely heavily on intermediates from their source countries. With a Japanese cost share averaging 21.8 percent in 2007, the production of U.S. affiliates of Japanese multinationals was highly exposed to the disruptions following the earthquake and tsunami. Yet, a large Japanese cost share is not sufficient for the transmission of the shock. For a given exposure, the degree to which a firm's production is affected by a shock to the supply

of intermediates depends on how substitutable these intermediates are with alternative inputs. The elasticity of substitution between inputs is therefore a critical determinant of the transmission of shocks.

We estimate this elasticity based on a reduced form exercise and a structural approach using the relative magnitudes of high frequency input and output shipments in the months following the Tōhoku earthquake/tsunami. Beginning with the reduced form exercise, we show that output of the average Japanese multinational affiliate fell, without a lag, by a magnitude comparable to the drop in imported inputs. When interpreted through the lens of a production function of a representative firm, this result implies a near-zero elasticity. We argue below that this estimate is informative for the calibration of international business cycle models with short-lived shocks as well as for understanding transition periods after unanticipated long-lived shocks.

Second, and to obtain firm-level elasticities, we structurally estimate a production function that allows for substitution across different inputs. In contrast to much of the empirical trade literature which estimates elasticities on the basis of first order conditions (see Feenstra et al., forthcoming), we estimate the production function *directly* as is common practice in industrial organization. We find this estimation strategy preferable for short-lived shocks such as the Japanese earthquake and tsunami. For instance, we show that measured Japanese input prices—both intra-firm and arms-length—did not change following the tsunami despite the clear incidence of a supply shock. The measured prices of these transactions were therefore likely not allocative, rendering the common approach based on first-order conditions problematic.

The structural estimates at the firm level are broadly in agreement with the reduced form evidence. For Japanese multinationals, the elasticity of substitution across material inputs is 0.2 and the elasticity between material inputs and a capital/labor aggregate is 0.03. For non-Japanese firms using inputs from Japan these estimates are similar. The elasticity of substitution across material inputs ranges from 0.42 to 0.62, and the elasticity between material inputs and capital/labor is also around 0.03. While the high cost shares of Japanese affiliates explain their predominant contribution to the direct transmission of this shock to the U.S., the elasticity estimates across all groups of firms are substantially lower than those typically used in the literature.

There are a number of important implications arising from a low elasticity of substitution between home and foreign inputs. This parameter appears in various forms in a wide span of models involving the exchange of goods across countries. As discussed by Backus, Kehoe, and Kydland (1994) and Heathcote and Perri (2002), among others, this elasticity is critically important for the ability of international real business cycle (IRBC) models to match key patterns of the data. Reflecting the uncertainty of available estimates, it is common practice to evaluate the behavior of these models along a wide range of parameter values. In a companion paper we demonstrate that a low degree of substitutability brings GDP comovement in an otherwise standard IRBC model closer to what is observed in the data (Boehm, Flaaen, and Pandalai-Nayar, 2014). This correlation increases by 11 percentage points when the elasticity of substitution of inputs is near zero relative to a baseline in which vertical linkages are absent.

While we estimate and discuss the role of this elasticity for the international transmission of shocks, this parameter is relevant for production networks more generally. Barrot and Sauvagnat (2016) show that a network model calibrated with a low elasticity better fits measured output losses after shocks. In our data, the strong complementarity across material inputs implied that non-Japanese imported input use also fell nearly proportionately, thereby propagating the shock to other upstream firms. Many suppliers were thus indirectly exposed to the shock via linkages with Japanese affiliates. Network effects such as these can substantially amplify the impact of the shock (both across countries and within). Indeed, in related work Carvalho et al. (2014) and Barrot and Sauvagnat (2016) provide evidence that firms that are only indirectly (i.e. through input linkages) affected by a shock also experience output losses.

The fact that low elasticities imply the transmission of shocks through production networks also has implications for aggregate volatility. A growing literature argues that shocks at the firm level can account for a non-trivial share of business cycle fluctuations (e.g. Carvalho and Gabaix, 2013). The fat-tailed firm size distribution is critical for explaining this fact (Gabaix, 2011). In our data, although the number of Japanese multinationals is small, their Japanese imports comprise a large share of the total. In addition to their size characteristics, however, input linkages and strong complementarities were important—these linkages served as a vehicle for the the transmission of

the shock to the U.S. where manufacturing production fell by about one percent (see also Atalay, 2017 and di Giovanni, Levchenko, and Mejean, 2014).

As is the case with most research based on specific events, care should be taken in generalizing the results to other settings. Ruhl (2008) emphasizes that the elasticity of substitution is necessarily tied to the time horizon and nature of shocks to which it is applied. As noted earlier, our structural estimates are most applicable for short-lived shocks and transition periods after unanticipated, long-lived shocks.¹ Further, one might worry that the composition of Japanese trade or firms engaged in such trade is not representative of U.S. trade linkages overall. We believe that our results are informative beyond the context of this particular episode for several reasons. First, the features of Japanese multinationals underlying the transmission of this shock are common to all foreign multinational affiliates in the U.S. Second, estimates for all firms in our sample also exhibit substantial complementarities, and as a whole these firms account for over 70 percent of U.S. manufacturing imports. Finally, supply chain disruptions are common: Over one-quarter of surveyed executives reported a supply chain disruption due to severe weather in the previous year. Other supply chain disruptions were also common (see The Economist Intelligence Unit, 2009).

The next section describes the relevant features of the Tōhoku earthquake and tsunami as well as the data sources used in this paper. Section 3 presents reduced form evidence in support of a low elasticity of substitution for Japanese multinational affiliates. In Section 4, we estimate firm-level elasticities in a structural model for several firm subgroups. Section 5 discusses the implications of these estimates, robustness, and external validity. The final section concludes.

2 Background and Data

This section outlines the background of our event-study framework based on the 2011 Tōhoku earthquake and tsunami. We discuss the relevant details of this shock, document its effects in aggregate time series, and present the data underlying the subsequent empirical analysis.

¹Although our natural experiment is uninformative about the elasticity of substitution in the long run, it has been argued that complementarities also play a key role in economic development (see, e.g. Kremer, 1993 and Jones, 2011).

2.1 Background

The Tōhoku earthquake and tsunami took place off the coast of Northeast Japan on March 11, 2011. It had a devastating impact on Japan, with estimates of almost twenty thousand dead or missing (Schnell and Weinstein, 2012) and substantial destruction of physical capital. The magnitude of the earthquake was recorded at 9.0 on the moment magnitude scale (M_w), making it the fourth largest earthquake recorded in the modern era.² Most of the damage and casualties were a result of the subsequent tsunami that inundated entire towns and coastal fishing villages. The effects of the tsunami were especially devastating in the Iwate, Miyagi, and Fukushima prefectures. The Japanese Meteorological Agency published estimates of wave heights as high as 7-9m (23-29ft), while the Port and Airport Research Institute (PARI) cite estimates of the maximum landfall height of between 7.9m and 13.3m (26-44ft).

Figure 1 shows the impact of the Tōhoku event on the Japanese economy. Japanese manufacturing production fell by roughly 15 percent in March 2011, and did not return to trend levels until July. Much of the decline in economic activity resulted from power outages that persisted for months following damage to several power plants—most notably the Fukushima nuclear reactor. Further, at least six Japanese ports (among them the Hachinohe, Sendai, Ishinomaki and Onahama) sustained damage and were out of operation for more than a month, delaying shipments to both foreign and domestic locations. It should be noted, however, that the largest Japanese ports (Yokohama, Tokyo, Kobe) which account for the majority of Japanese trade, re-opened only days after the event.

As expected, the economic impact of the event was reflected in international trade statistics, including exports to the United States. Figure 2 plots U.S. imports from Japan around the period of the Tōhoku event, with imports from the rest of the world for comparison. The large fall in Japanese imports occurs during the month of April 2011, reflecting the several weeks of transit time for container vessels to cross the Pacific Ocean. The magnitude of this drop in imports is roughly similar to that of Japanese manufacturing production: a 20 percent drop in April, with a

²Since 1900, the three earthquakes of greater recorded magnitude are: the 1960 Great Chilean earthquake (magnitude 9.5); the 1964 Good Friday earthquake in Prince William Sound, Alaska (magnitude 9.2); and the 2004 Sumatra-Andaman earthquake (magnitude 9.2).

recovery by July 2011.

Particularly striking is the impact on the U.S. economy in the months following the shock. Figure 3 demonstrates that there is indeed a drop in U.S. manufacturing production. Although the magnitudes are much smaller—roughly a one percent drop in total manufacturing and almost two percent in durable goods—there is clearly a measurable macroeconomic effect.³

Though tragic, the Tōhoku event provides a rare opportunity to study the cross-country spillovers following an exogenous supply shock. This natural experiment features many characteristics that are advantageous for our study. It was large and hence measurable, unexpected, and directly affected only one country. On the other hand, the short duration of the shock presents a challenge as it limits the available datasets with information at the required frequency.

2.2 Data

Several restricted-use Census Bureau datasets form the core of our analysis. The Longitudinal Business Database (LBD) collects the employment, payroll, and industry of nearly all private non-farm establishments operating in the United States, and is maintained and updated as described by Jarmin and Miranda (2002). Longitudinal linkages allow the researcher to follow establishments over time, and the annual Company Organization Survey (COS) provides a mapping from establishments to firms. Unless otherwise noted the analysis in this paper will be at the firm-level.

The Longitudinal Foreign Trade Transactions Database (LFTTD) links individual trade transactions to firms operating in the United States. Assembled by a collaboration between the U.S. Census Bureau and the U.S. Customs Bureau, the LFTTD contains information on the destination (or source) country, quantity and value shipped, the transport mode, and other details from point-of-trade administrative documents. Importantly for this study, the LFTTD includes trade transactions at a *daily* frequency, which are easily aggregated to monthly flows.

We make two novel extensions to this set of Census data products. First, a new link between two international corporate directories and the Business Register (BR) of the Census Bureau provides information on the international affiliates of firms operating in the United States. These directories

³At the level of total U.S. GDP, both Deutsche Bank and Goldman Sachs revised 2nd quarter U.S. estimates down by 50 basis points explicitly due to the events in Japan (see Cox (2011)).

allow us, for the first time, to identify the U.S. affiliates owned by a foreign parent company, as well as those U.S. firms with affiliate operations abroad. This information is an important resource for identifying the characteristics of U.S. firms affected by the Tōhoku event.⁴ Appendix Figure B1 shows the affiliate locations in Japan together with an earthquake intensity measure. A large number of firms were indeed located in regions that were strongly affected by the earthquake and tsunami.

Second, we develop a system to classify firm-level import transactions as intermediate or final goods. Although intermediate input trade represents as much as two-thirds of total trade (see Johnson and Noguera, 2012), the LFTTD does not classify a trade transaction by its intended use. To overcome this limitation, we use information on the products produced by U.S. establishments in a given industry to define a set of products intended for final sale *for that industry*.⁵ The remaining products are presumably used by establishments in that industry either as intermediate inputs or as capital investment. Details on this classification procedure are available in Appendix A.2. In the aggregate, this classification procedure yields values of the intermediate share of trade that are consistent with prior estimates: 64 percent of manufacturing imports are classified as intermediates in 2007.

The ideal dataset to evaluate the transmission of the Tōhoku event to U.S. firms would consist of high frequency information on production, material inputs, and trade, separated out by geographic and ownership criteria. Information from the LFTTD on import shipments is ideal for these purposes. Census data on production and domestic material usage, however, is limited. The Annual Survey of Manufacturers (ASM) contains such information, but at an annual frequency and only for a subset of manufacturing firms. Recognizing the challenges of obtaining high-frequency information on firms' U.S. production, we utilize a proxy based on the LFTTD—namely the firm's exports of goods to North America (i.e. Canada and Mexico). There are few barriers to North American trade, and transport time is relatively short. Moreover, as documented in Flaaen (2014), exporting is a common feature of multinationals, of which exports to North America is by far the

⁴For information on these directories and the linking procedure, see Flaaen (2014) and Appendix A.1.

⁵Notice that we distinguish between intermediate and final goods from the perspective of an importing firm. For example, this classification does not rule out that the final goods of one firm are used as intermediates by another firm in a different industry.

largest component. This fact alleviates concerns arising from conditioning on a positive trading relationship. We demonstrate in Section 5.1.1 that the quality of this proxy for output is high. In a separate dataset containing high-frequency information on production for a smaller set of firms, we show that actual output tracks our proxy very closely.

3 Reduced-Form Evidence

In this section we present evidence on the behavior of firms around the Tōhoku event. We document that the production of Japanese affiliates in the U.S. fell, on average, roughly one-for-one with imported intermediates from Japan. We then interpret this behavior through the lens of a production function of a representative firm and conclude that the substitutability of Japanese-produced intermediates with other inputs is very low. While this section focuses on the average (or aggregate) effect, which informs the calibration of production elasticities in IRBC and other macro models, we estimate firm-level elasticities in the next section.

3.1 Framework

To study the transmission of the Tōhoku shock we compare the behavior of directly affected firms in the U.S. to a control group of firms that were not directly affected. A natural measure for a firm's exposure to the shock is its share of Japanese imported inputs in total costs prior to the Tōhoku event. We construct this measure by taking Japanese imported inputs and dividing by all other inputs (this includes production worker wages and salaries, the cost of materials, and the cost of new machinery expenditures). Exposure to Japanese imported inputs is heavily concentrated among U.S. affiliates of Japanese multinationals. In the year 2007, which is the closest available Census year for which this measure can be constructed, the cost share averaged nearly 22% for Japanese-owned affiliates (see Panel A of Table 1), compared to just 1% for other firms. To better understand the heterogeneity within and across these firm groups, we construct a density estimate of cost shares for Japanese affiliates and non-Japanese multinationals. The results, shown in Figure 4, show little overlap between these two distributions: there are few Japanese affiliates with low

exposure to Japanese inputs, and few non-Japanese firms with substantial exposure.⁶ We conclude that Japanese ownership accurately captures the set of firms with high exposure to the supply chain disruption.

These large differences in exposure suggest a simple and transparent identification strategy. We implement a dynamic treatment effects specification in which a firm is defined as being treated if it is owned by a Japanese parent at the time of the shock.⁷ The control group, which we discuss below, serves to soak up common seasonal patterns and demand-driven factors in the U.S. market. While there are a number of competing methodologies for this type of estimation, we use normalized propensity score re-weighting due to the relatively favorable finite-sample properties as discussed in Busso, DiNardo, and McCrary (2014).

Consistent estimation of the average treatment effect on the treated requires the assumption of conditional independence: the treatment/control assignment is independent of potential outcomes conditional on a set of variables. As the average Japanese firm differs considerably from other firms in the data, we use other multinational firms—both US and non-Japanese foreign—as our control group prior to re-weighting. We construct the propensity scores using information on firm size and industry. Table 1 reports summary statistics for the sample, including test results showing that post re-weighting, the treatment and control groups are indeed comparable along these dimensions.⁸

In addition to the conditional independence assumption, consistent estimation of the mean effect requires that the control group is not itself impacted by the shock. This Stable Unit Treatment Value Assumption necessitates that general equilibrium effects and the effects of strategic interaction are small or absent. As shown earlier, the total effect on U.S. manufacturing production is approximately 1 percent. This includes the direct effect on Japanese multinationals and is therefore an upper bound on possible general equilibrium effects. In contrast, the effect we will measure at the firm level is more than an order of magnitude higher. Additionally, we show in Section 5.1.5

⁶The exposure measure used in Figure 4 is from 2010. Because 2010 is not a Census year, the exposure measure does not include the cost of domestic material usage.

⁷We have also tried a threshold of Japanese input usage for the classification of treatment status. Due to the almost perfect separation illustrated in Figure 4, this procedure yields very similar estimates.

⁸Note that re-weighting does not change the relative exposure to the shock in Japan: The fraction of Japanese imported inputs in total imported inputs is 70% for Japanese and only 3.5% for non-Japanese multinationals (see Table 1).

that for a group of non-Japanese firms for which detailed data is publicly available, there were no measurable production responses after the shock, despite the fact that their Japanese counterparts suffered large declines in output. We thus feel confident that neither general equilibrium effects, nor strategic interaction with direct competitors adversely affect our estimation.

The magnitude of the shock for a representative Japanese multinational is captured by the effect on *total* imported intermediate inputs. Let $V_{i,t}^M$ be the value of intermediate imports of firm i in month t , after removing a firm-specific linear trend through March 2011. We estimate the specification

$$V_{i,t}^M = \alpha_i + \sum_{\tau=-19}^9 \gamma_{\tau} E_{\tau} + \sum_{\tau=-19}^9 \beta_{\tau} E_{\tau} JPN_i + u_{i,t}, \quad (1)$$

where α_i is a firm fixed-effect, γ_{τ} a month fixed effect (with the indicator variables E_{τ} corresponding to the calendar-months around the event), JPN_i is a Japanese multinational indicator, and $u_{i,t}$ is an error term. We denote March 2011 as $t = 0$. The sample comprises manufacturing firms only (for details see Appendix A.3).

The β_{τ} coefficients are of primary interest. Interacting the JPN_i indicators with month indicators around the shock allows for a time-varying effect of the disruption in Japan on a firm's overall intermediate input imports. The β_{τ} coefficients will estimate the differential effect of the Tōhoku event on Japanese affiliates, compared to the control group of non-Japanese firms. To evaluate the differential impact on production for Japanese firms, we simply replace the dependent variable in equation (1) with North American exports, denoted $V_{i,t}^{NA}$.

We estimate specification (1) in levels. By doing so, we estimate the mean decline in imports relative to the control group (ΔV^M). To obtain percent changes we will later divide this difference by the average pre-shock level of imports. Relative to an estimation in logs, the estimation in levels does not necessitate dropping observations with zero imports in a given month—which is critical in the aftermath of the Tōhoku shock. At the monthly frequency, many firms could have zero imports, and this is particularly true after the supply chain disruption. Dropping these observations would systematically remove those firms most affected by the shock and thereby bias the difference ΔV^M towards zero. In Appendix B.2 we discuss an alternative specification. Our main conclusions are robust.

3.2 Results

The top panel of Figure 5 plots the β_τ coefficients from equation (1) for the months around the Tōhoku event. Relative to the control group, there is a large drop in total intermediate input imports by Japanese firms in the months following the earthquake. The drop in intermediates bottoms out at roughly 4 million USD per firm in $t = 3$ (June 2011) and the point estimates do not return back to the pre-shock trend until month $t = 7$ (October 2011).

Panel B of Figure 5 displays the impact on production of this shock on Japanese firms as proxied by their North American exports. This differential time-path also exhibits a substantial drop following the Tōhoku event, hitting a trough of 2 million USD below baseline in $t = 2$ (May 2011). Both panels in Figure 5 show 95-percent confidence bands, based on standard errors that are clustered at the firm level. These standard errors widen substantially upon impact, reflecting the heterogeneous incidence of and recoveries from the shock across Japanese multinationals.

To compare the average percent drop in imports and production, we take the series of β_τ and divide by the average pre-shock level for these firms (see Table 1). The results, plotted jointly in Figure 6, show a remarkable correlation. There is essentially a one-for-one drop in output for a given drop in intermediate input imports.⁹

The analysis up to here has been carried out in trade values (price times quantity). To understand how the observed responses reflect changes in the underlying quantities and prices, we turn to the response of unit values (value divided by quantity, see Appendix B.3 for details). On the one hand, one would expect price increases due to the negative supply shock. On the other hand, the Bank of Japan's response to the earthquake/tsunami resulted in a brief Yen depreciation relative to the U.S. dollar, implying a downward adjustment in dollar-denominated prices.¹⁰ To evaluate whether Japanese imports prices systematically changed during this time, we estimate the

⁹There was no differential effect on exports from the U.S. to Japan for these firms. See Appendix B.4.

¹⁰More precisely, the Yen/dollar exchange rate experienced several brief adjustments after the earthquake and tsunami. Relative to its value on March 10, the Yen first appreciated for about 2 weeks, then depreciated for a month, and then appreciated again. When averaged to the monthly level, these exchange rate movements are modest, in the order of 2 to 3 percent. We plot the exchange rate around the Tōhoku shock in Appendix Figure B2.

specification

$$\log P_{i,k,t} = \alpha_{i,k} + \sum_{\tau=-19}^9 \gamma_{\tau} E_{\tau} + \sum_{\tau=-19}^9 \beta_{\tau} E_{\tau} JPN_{i,k} + u_{i,k,t}, \quad (2)$$

where $P_{i,k,t}$ is the average unit value of Japanese imported inputs within an HS-10 products category, indexed k , of firm i at time t . Relative to our specification (1) above, the indicator $JPN_{i,k}$ takes the value one for imports from Japan, rather than by Japanese firms. Price changes of Japanese imports over time will be reflected in γ_{τ} and differential changes for Japanese multinationals in β_{τ} . We also estimate this specification for the unit values of North American exports (in which case $JPN_{i,k}$ is again a dummy variable for Japanese multinationals).

Table 2 shows the coefficient estimates. We keep related-party and arms-length transactions separate as one might expect these prices to behave differently following a shock. We do not observe consistently positive or negative responses for either imports or exports and the estimates are small in absolute terms. We therefore conclude that dollar-denominated price adjustments played a negligible role in the aftermath of the Japanese earthquake and tsunami. This implies that the observed responses in import and export values largely reflect quantity adjustments.¹¹

3.3 Interpretation

We interpret these findings through the lens of a representative Japanese multinational firm with a standard constant elasticity of substitution (CES) production function. Suppose that this firm produces output x from a domestic bundle of factors F_D (e.g. capital and labor) and an imported intermediate IM ,

$$x = \left[(1 - \mu)^{\frac{1}{\psi}} [F_D]^{\frac{\psi-1}{\psi}} + \mu^{\frac{1}{\psi}} [IM]^{\frac{\psi-1}{\psi}} \right]^{\frac{\psi}{\psi-1}}. \quad (3)$$

Parameter ψ is the elasticity of substitution between the two inputs—the object of interest in this section—and μ is the relative weight of input IM . This production function implies that the

¹¹This finding is consistent with the publicly available time series of Japanese import prices from the International Price Program of the Bureau of Labor Statistics. This time series does not display any unusual movements around March 2011.

elasticity of output with respect to imported intermediates is

$$\frac{d \ln x}{d \ln IM} = \Lambda \left(\frac{F_D}{IM}, \mu, \psi \right) + \left(1 - \Lambda \left(\frac{F_D}{IM}, \mu, \psi \right) \right) \frac{d \ln F_D}{d \ln IM}, \quad (4)$$

where $\Lambda \left(\frac{F_D}{IM}, \mu, \psi \right) = \left(\frac{F_D}{IM} \left(\frac{IM/\mu}{F_D/(1-\mu)} \right)^{\frac{1}{\psi}} + 1 \right)^{-1} \in (0, 1)$. Hence, fewer intermediates in production imply a direct effect on output of size Λ and an indirect effect of size $1 - \Lambda$ resulting from the adjustment of other inputs F_D . We assume in this section that firms' U.S. productivity was not directly impacted by the shock in Japan and there is no variable factor utilization. We will return to both of these issues in sections 4 and 5.

We next translate the output elasticity of roughly one into a value for the elasticity of substitution ψ . Suppose for the moment that $\frac{d \ln F_D}{d \ln IM}$ was smaller than unity. That is, there is a less than one-for-one adjustment of capital/labor with the fall in intermediate input imports. Then equation (4) implies that Λ must be near one. This can only be the case if *both* (1) $IM/\mu < F_D/(1 - \mu)$ and (2) $\psi \rightarrow 0$. In words, the measured output elasticity combined with a less than one-for-one adjustment of F_D would imply that the production function (3) is Leontief and imports are the factor limiting the firm's production.¹² Formally,

$$\lim_{\psi \rightarrow 0} \frac{d \ln x}{d \ln IM} = \mathbf{1} \{IM/\mu < F_D/(1 - \mu)\} + \mathbf{1} \{IM/\mu > F_D/(1 - \mu)\} \lim_{\psi \rightarrow 0} \frac{d \ln F_D}{d \ln IM},$$

where $\mathbf{1} \{ \cdot \}$ denotes the indicator function.

This analysis shows that it is necessary to understand the magnitude of adjustment of domestic inputs F_D after the Tōhoku event. We therefore re-estimate specification (1) after replacing the left-hand side with measures of firms' employment and payroll. Table 3 shows the results, now for a quarterly sample.¹³ There is no evidence of a reduction of the workforce or payroll in the aftermath of the Tōhoku event. This lack of adjustment is not surprising given the wealth of evidence for the presence of adjustment costs, in particular at short time horizons (see e.g. Bloom, 2009). Although we do not observe firms' capital stocks at high frequencies, there is virtually no

¹²This argument can easily be extended to a C.E.S. production function with more than two inputs. We discuss alternative levels of aggregation of intermediate inputs in Sections 4.1 and 5.1.6

¹³See Appendix B.5 for more details on the sample creation for domestic employment and payroll.

scope for adjustments along this margin. The facts that 1) capital is a stock while investment is a flow, and 2) investment is also subject to adjustment costs, imply that the capital stock is essentially constant in the short run (see House and Shapiro, 2008). It must therefore be the case that $\frac{d \ln F_D}{d \ln IM}$ was smaller than 1.

Our reduced-form evidence thus indicates that at the macroeconomic level, the behavior of Japanese-owned affiliates can best be rationalized by a production function with an elasticity of substitution near zero. The supply of key materials was disrupted and alternatives were not available at finite prices.

Finally, it is worth highlighting that anecdotal evidence supports our empirical results, in particular that Japanese inputs were the limiting factor in U.S. production and that employment did not adjust after the shock. To take an example, according to an April 8, 2011 press release from Toyota North America: “Toyota is adjusting North American production due to parts availability following the March 11 Japan earthquake” where “... the company will continue to provide employment for its approximately 25,000 regular North American team members ...” Another telling statement came from a Toyota spokesman around the same time: “Toyota only gets about 15 percent of its parts from Japan for cars and trucks built in North America, but still you have to have them all to build the vehicles.”¹⁴ Other news reports and press releases universally attributed the U.S. production impacts to shortages of parts coming from Japan.¹⁵

4 Structural Estimation

As the reduced form evidence in Section 3 showed, the relative movements of imported inputs and output point to little substitutability of intermediates. We continue our analysis by structurally estimating the production function at the firm-level. This estimation serves multiple purposes. First, we address concerns about aggregation by showing that firm-level elasticities are consistent with the average behavior we documented in the previous section. Second, by adding further structure, we can distinguish two elasticities: one between Japanese material inputs and other material

¹⁴See Associated Press (2011) for the full quote.

¹⁵Note that we do not know and would not be permitted to state whether Toyota or any other firm is included in any of our Census-based samples.

inputs, and another between an aggregate bundle of material inputs and a domestic aggregate of capital and labor. Finally, by using an estimation procedure that does not rely on a control group we obtain separate estimates for Japanese and non-Japanese firms. The results for these groups are similar, reinforcing the main conclusion that the substitutability of inputs is small in the short run.

4.1 Framework

We assume that firms' technologies are given by a nested CES aggregate

$$x_{i,t} = \phi_i \left[\mu_i^{\frac{1}{\zeta}} (K_{i,t}^\alpha L_{i,t}^{1-\alpha})^{\frac{\zeta-1}{\zeta}} + (1 - \mu_i)^{\frac{1}{\zeta}} M_{i,t}^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}}, \quad (5)$$

where

$$M_{i,t} = \left[\nu_i^{\frac{1}{\omega}} (m_{i,t}^{-J})^{\frac{\omega-1}{\omega}} + (1 - \nu_i)^{\frac{1}{\omega}} (m_{i,t}^J)^{\frac{\omega-1}{\omega}} \right]^{\frac{\omega}{\omega-1}}. \quad (6)$$

In this production function $x_{i,t}$, $K_{i,t}$, and $L_{i,t}$ denote the output, capital, and labor of firm i . The variable $M_{i,t}$ denotes an aggregate of materials sourced from Japan ($m_{i,t}^J$) and materials sourced from all places other than Japan ($m_{i,t}^{-J}$), including domestic materials.¹⁶ We are interested in estimating ω , which parameterizes the substitutability between Japanese and non-Japanese materials and ζ , the elasticity of substitution between the capital-labor aggregate and the aggregate of material inputs. The parameters μ_i and ν_i are weights and ϕ_i parameterizes firm i 's productivity in the United States.¹⁷ Further, we assume that the firm is monopolistically competitive and faces a CES demand function

$$p_{i,t}^x = \left(\frac{Y_{i,t}}{x_{i,t}} \right)^{\frac{1}{\varepsilon}}. \quad (7)$$

As usual, $Y_{i,t}$ is the bundle used or consumed downstream and serves as a demand shifter beyond the control of the firm.

In what follows, we estimate the production function directly from the variation of inputs and

¹⁶Notice that this assumption does not imply that the inputs *within* the Japanese and non-Japanese bundles are perfectly substitutable with one another as long as these inputs are chosen optimally. We choose this level of aggregation because a more detailed breakdown would increase measurement error at this frequency. Our approach attempts to balance this concern with the benefit of allowing the identification of an elasticity between two bundles of intermediates. See Section 5.1.6 for further details.

¹⁷In the estimation that follows we assume that μ_i and ν_i are constant within an industry.

outputs rather than using an approach based on first order conditions. We find this approach preferable in our context for two reasons. First, the essence of the common approach in the trade literature (see Feenstra et al., forthcoming) is to regress relative trade values on relative prices. As we showed above, there was no significant response of measured prices in the aftermath of the Tōhoku disruption. This 1) limits the available identifying variation and 2) casts doubt on whether the measured prices were actually allocative in the period after the shock. Second, the common approach is most suitable for low-frequency data. In the short run, however, dynamic aspects of optimization such as adjustment costs cannot be ignored. A possibility is then to model these costs explicitly, but doing so would complicate the estimating equation and increase the number of parameters to estimate. Below we will discuss in detail the assumptions that our estimation approach requires.

Our estimation proceeds in two steps. In an initial period immediately prior to the Tōhoku disruption, denoted $\tau - 1$, we infer information on the firm's productivity ϕ_i as well as the weights μ_i and ν_i . This part of the estimation *does* rely on first order conditions. Then, using this information in the period of the disruption, τ , we estimate the elasticity parameters based on how firms' output depends on their input use. In this second period τ we do not rely on first order conditions. Period $\tau - 1$ corresponds to the months from September 2010 to February 2011, and τ to the months from April to September 2011. We exclude March 2011.

4.1.1 Pre-Tsunami period

In period $\tau - 1$ the firm operates in a stable environment that is well-modeled by a standard static optimization problem. The firm chooses capital, labor, and materials to maximize

$$p_{i,\tau-1}^x x_{i,\tau-1} - w_{\tau-1} L_{i,\tau-1} - R_{\tau-1} K_{i,\tau-1} - p_{i,\tau-1}^{-J} m_{i,\tau-1}^{-J} - p_{i,\tau-1}^J m_{i,\tau-1}^J$$

subject to (5), (6), and (7). The firm takes all factor prices as given. Material prices $p_{i,\tau-1}^J$ and $p_{i,\tau-1}^{-J}$ are firm-specific to indicate that different firms use different materials. This optimization

problem implies the following relationships:

$$K_{i,\tau-1} = \frac{\alpha}{1-\alpha} \frac{w_{\tau-1} L_{i,\tau-1}}{R_{\tau-1}}, \quad (8)$$

$$\nu_i = \frac{(p_{i,\tau-1}^{-J})^\omega m_{i,\tau-1}^{-J}}{(p_{i,\tau-1}^J)^\omega m_{i,\tau-1}^J + (p_{i,\tau-1}^{-J})^\omega m_{i,\tau-1}^{-J}}, \quad (9)$$

$$\mu_i = \frac{\left(\left(\frac{R_{\tau-1}}{\alpha}\right)^\alpha \left(\frac{w_{\tau-1}}{1-\alpha}\right)^{1-\alpha}\right)^\zeta K_{i,\tau-1}^\alpha L_{i,\tau-1}^{1-\alpha}}{(P_{i,\tau-1}^M)^\zeta M_{i,\tau-1} + \left(\left(\frac{R_{\tau-1}}{\alpha}\right)^\alpha \left(\frac{w_{\tau-1}}{1-\alpha}\right)^{1-\alpha}\right)^\zeta K_{i,\tau-1}^\alpha L_{i,\tau-1}^{1-\alpha}}, \quad (10)$$

where

$$P_{i,\tau-1}^M = \left[\nu_i (p_{i,\tau-1}^{-J})^{1-\omega} + (1-\nu_i) (p_{i,\tau-1}^J)^{1-\omega} \right]^{\frac{1}{1-\omega}}.$$

4.1.2 Post-Tsunami period

It is clear that a static optimization problem is unsuitable for modeling the short-run behavior of the firm immediately after the shock. Rather, and as we showed in Section 3.3, adjustment costs and possibly other dynamic considerations limited firms' adjustment of labor. To accommodate these concerns we only use the production function of the firm for estimation, as it is independent of the form and the presence of adjustment costs as well as other dynamic considerations. Conditional on knowing ν_i , μ_i , and ϕ_i which we back out from equations (9), (10), and (14) below, we estimate the elasticity parameters ζ and ω from how the firms' output co-varies with its inputs. We assume that in period τ , firms operate the same production function given by (5) and (6), and that no firm adjusts its capital stock such that $K_{i,\tau} = K_{i,\tau-1}$.¹⁸

4.2 Estimation

Recall that in Section 3 we used North American exports as a proxy for a firm's output $p_{i,t}^x x_{i,t}$, with the underlying assumption that they are proportional to one another. We continue here in the same spirit, though we now make this assumption explicit. Let $V_{i,t}^{NA}$ be the value of North American

¹⁸We have relaxed this assumption in robustness checks by assuming that equation (8) continues to hold in period τ . The results are similar.

exports at time t and define

$$\kappa_i = \frac{V_{i,\tau-1}^{NA}}{p_{i,\tau-1}^x x_{i,\tau-1}}. \quad (11)$$

In words, κ_i is the fraction of firm i 's shipments exported to Canada and Mexico in the six months preceding the disruption. We next assume that the same relationship continues to hold in period τ , except for a log-additive error $u_{i,\tau}$. That is,

$$\ln V_{i,\tau}^{NA} = \ln \kappa_i p_{i,\tau}^x x_{i,\tau} + u_{i,\tau} \quad (12)$$

$$= \ln(\kappa_i \phi_i) + \ln \left(p_{i,\tau}^x \left[\mu_i^{\frac{1}{\zeta}} \left(K_{i,\tau}^\alpha L_{i,\tau}^{1-\alpha} \right)^{\frac{\zeta-1}{\zeta}} + (1 - \mu_i)^{\frac{1}{\zeta}} \left(M_{i,\tau} \right)^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}} \right) + u_{i,\tau}, \quad (13)$$

where the second equality uses production function (5).

Equation (13) is our estimating equation. Values for ν_i and μ_i are obtained from equations (9) and (10). Using (11), the intercept can be constructed from the previous period

$$\kappa_i \phi_i = \frac{V_{i,\tau-1}^{NA}}{p_{i,\tau-1}^x \left[\mu_i^{\frac{1}{\zeta}} \left(K_{i,\tau-1}^\alpha L_{i,\tau-1}^{1-\alpha} \right)^{\frac{\zeta-1}{\zeta}} + (1 - \mu_i)^{\frac{1}{\zeta}} \left(M_{i,\tau-1} \right)^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}}}. \quad (14)$$

Notice that κ_i and ϕ_i are not separately identified. We estimate the elasticities ζ and ω in equation (13) by nonlinear least squares. That is, the estimates $(\hat{\zeta}, \hat{\omega})$ solve $\min_{\{\zeta, \omega\}} \sum_{i=1}^N (u_{i,\tau})^2$.

Consistent estimation requires that $\mathbb{E}[u_{i,\tau}|X_i] = 0$, where X_i is a vector of all right-hand-side variables. This exogeneity assumption rules out, for example, that after the fall in Japanese intermediate input imports, firms exported a fraction of their shipments to Canada and Mexico that systematically differed from κ_i . In Section 5.1.1 we provide evidence in support of this assumption.

A second critical assumption is that ϕ_i is constant. If not, its variation would be picked up by the error term, rendering our estimates inconsistent. We believe that the assumption that ϕ_i is constant is satisfied. First, our estimation focuses on a short time period, making large shocks other than the Japanese earthquake unlikely. Second, we can indirectly test whether the disruption impacted the U.S. productivity ϕ_i of Japanese firms, for instance, through an effect on their headquarters. Below, we estimate parameters ζ and ω for both Japanese and non-Japanese firms separately. A

possible headquarters effect should then only influence the estimates for Japanese-owned firms. Since our results are similar across all firms, it does not appear that ϕ_i was directly impacted by the shock.

To summarize: The behavior of firms in period $\tau - 1$ provides conditions that determine the values of ν_i , μ_i , and $\kappa_i\phi_i$. Then, in period τ , we observe how the variation in output across firms co-varies with their input use. This pins down the values of the elasticities ζ and ω .

Two key advantages of this estimation procedure are that 1) it does not require any assumptions on the *form* of adjustment costs faced by firms, and 2) it does not conflate the identification of the elasticities of substitution with these adjustment costs. To understand the latter point, notice that both the value of the elasticities and adjustment costs affect the choice of the input bundle in the firm's optimization problem. However, conditional on an observed input choice only the elasticities affect output. Since we directly estimate only the production function, we identify only the elasticity—based on how output depends on measured inputs.

4.3 Connecting Model and Data

Estimation of the model requires data on employment, payroll, the value of Japanese and non-Japanese material inputs, the value of exports to North America, as well as input and output prices, all for periods $\tau - 1$ and τ . Since data on firm-specific capital stocks are hard to obtain and likely noisy, we use equation (8) to construct it from firm payroll and a semi-annual rental rate of 7 percent for period $\tau - 1$. Recall that the capital stock is not adjusted over this time horizon so that $K_{i,\tau} = K_{i,\tau-1}$.¹⁹ We calibrate the capital share α to $1/3$ as is roughly the case for the aggregate U.S. economy. We note, however, that our estimates are robust to alternative values of α and the rental rate as well as to constructing the capital stock from equation (8) at time τ . This robustness presumably reflects the fact that there were no systematic adjustments in firm's labor inputs or payroll as we demonstrated in Section 3.3.

Quarterly employment and payroll information comes from the Business Register.²⁰ As dis-

¹⁹The 7 percent rental rate is based on an annual real rate of 4 percent, an annual depreciation rate of 10 percent.

²⁰We adjust employment to reflect the average value over the 6 month periods we study, which happen to align well with the timing of the earthquake. Specifically we set $L_{\tau-1} = \frac{1}{6}Emp_{2010Q3} + \frac{1}{2}Emp_{2010Q4} + \frac{1}{3}Emp_{2011Q1}$

cussed in earlier sections, the LFTTD contains firm-level data of Japanese imports and North American exports. For non-Japanese material inputs, we would ideally combine the data on non-Japanese imported materials with information on domestic material usage for these firms. As information on domestic material inputs is not available in Census data at this frequency, we utilize information on *total* material expenditures from the Census of Manufacturers (CM) to construct a firm-level scaling factor to gross up non-Japanese intermediate input imports. Put differently, we impute total non-Japanese material inputs from data on non-Japanese input imports. For each firm, we construct the scaling factor as

$$\frac{P_i^M M_i - p_i^J m_i^J}{p_i^J m_i^J} \quad (15)$$

from the latest CM year.²¹ We use unit values at the HS10 level from the LFTTD to construct firm-level price import and export price indexes.²²

Finally, we restrict the sample of firms to those that have regular imports from Japan and non-Japan over the periods we study, as well as regular North American exports.²³ While this limits the number of firms in each sample, the shares of trade represented by these firms in each category remains very high (see Table 4). We obtain standard errors using bootstrap methods, see Appendix B.7 for details.

4.4 Results

The results of the estimation are shown in Table 4. The elasticity between material inputs for Japanese affiliates is 0.2, while the elasticity between the aggregate material input and capital/labor is 0.03. Together, these estimates are indeed consistent with the evidence of little substitutability in Section 3.2. The relative magnitudes of the point estimates are also intuitive: while Japanese imported inputs are strong complements with other material inputs, there is even less scope for substitution between material inputs and domestic capital/labor.²⁴

and $L_\tau = \frac{1}{2}Emp_{2011Q2} + \frac{1}{2}Emp_{2011Q3}$, and analogously for payroll.

²¹We use industry-specific means for missing values, and winsorize large outliers at the 90th/10th percentiles.

²²Those transactions with missing or imputed quantity information are dropped.

²³Specifically, we drop any firm that has more than 3 months of zeros for any of these values, in period $\tau - 1$ or τ .

²⁴The point estimates notwithstanding, the confidence intervals do not rule out that ζ is higher than ω .

We next estimate these elasticities for two samples of non-Japanese firms: non-Japanese multinationals and non-multinational firms. The point estimates of elasticity ζ are virtually identical across all groups of firms, although we note that for the non-multinational sample, the estimate is too imprecise to rule out values above unity. To provide additional information we plot the density of the elasticity estimates across bootstrap samples in Appendix Figure B8. The estimates of ω are also very similar, ranging from 0.4 to 0.62 for non-Japanese affiliates. Taken together, the estimates for these parameters are significantly lower than what is commonly assumed in the literature (typically unity or higher). Finally, the fact that these estimates are similar across all firm groups indicates that there were no direct spillovers to productivity ϕ_i due, for example, to headquarter effects.²⁵

Although the number of firms included in this estimation is not large (550 firms in total across the three subgroups), they account for a large share of economic activity in the United States. Looking at their combined share of total trade, these firms account for over 80% of Japanese intermediate imports, 68% of non-Japanese intermediate imports, and well over 50% of North American exports. Such high concentration of trade among relatively few firms is consistent with other studies using this data (see Bernard et al., 2007).

5 Robustness, Implications and External Validity

Our empirical evidence uniformly points to little substitutability of inputs in the short run. In this section we discuss 1) the robustness of this conclusion, 2) implications for theoretical work in areas such as IRBC and network models, and 3) external validity.

²⁵As is clear from the confidence intervals for these estimates, we cannot rule out that the elasticity estimates are the same across all four samples.

5.1 Robustness

5.1.1 Evaluating the production proxy

A natural concern with our analysis is the use of North American exports as a proxy for production. Perhaps it was the case that export shipments fell disproportionately more than production following the shock. If this was true, then North American exports would overstate the impact on production and bias our elasticity estimates.

To evaluate the production proxy in the context of the event study, we focus on the automotive sector for which production at the monthly frequency is available from the Ward's electronic databank.²⁶ Similar to our analysis in Section 3, we construct a series measuring how much auto production of Japanese automakers fell relative to that of non-Japanese automakers around the time of the Tōhoku shock. This series is shown in Figure 7 together with our production proxy (North American exports). It is remarkable how closely production tracks our proxy, despite the fact that the series for North American exports covers a very different set of firms (all U.S. affiliates of Japanese multinationals). Both series fall sharply in April 2011. Both series bottom out in May ($t = 2$), reaching troughs of 55 and 53 percent. And both series begin to recover thereafter, returning to zero in September 2011.

We also calculate the correlation of annual growth rates from 2007 to 2011 between shipments (as measured by the ASM and CM) and North American Exports at the firm-level in our data. These unconditional (export weighted) correlations are high, ranging from 0.58 for multinational firms in our sample to 0.68 for the Japanese multinationals.

5.1.2 Inventories

Inventories of intermediate inputs allow firms to absorb unforeseen shocks to input deliveries without an impact on production. In the period after the disruption the presence of such inventories would serve to diminish or delay the production impact. As a result our estimation procedure, which does not explicitly take into account inventory accumulation, would bias the estimates *upwards*, stacking the odds against finding a low elasticity. In fact, the extent to which we do not see

²⁶See Appendix B.9 for further details.

any evidence of meaningful inventories of intermediate inputs is striking. In Figures 5 (Panel B) and 7 the impact on production is almost immediate.

We obtain a rough sense of the prevalence of inventory holdings from the closest available Census of Manufacturers in 2007. Combining information on the beginning of period stock of materials inventories with the annual usage of materials, we calculate the months' supply of inventories. Table 6 shows the production weighted averages for Japanese multinationals and non-multinational firms.²⁷ Japanese multinationals hold a little over 3-weeks worth of intermediate inputs as inventory. This is slightly less than non-multinational firms, a fact that aligns well with the oft-cited "just-in-time" production philosophy pioneered by Japanese firms. Table 6 also reports the corresponding estimates for output inventories. They are uniformly low.

The observations that 1) input inventory holdings are low and 2) that these inputs are highly complementary in the short run suggest that firms are willing to incur a nontrivial risk of production disruption. A direct implication is that such production strategies will increase the propagation of shocks through production networks. We discuss propagation effects further in Section 5.2.

5.1.3 Strategic Behavior of Competitors

Our treatment effects specification in Section 3 requires that the control group is unaffected by the shock. If competitors of Japanese multinationals increased production in response to the shock, our estimates would overstate its impact on the output for Japanese multinationals. To evaluate this possibility, we return to the Ward's automotive data and consider the behavior of non-Japanese automakers in the months directly following the Tōhoku event. Appendix Figure B3 plots production separately for Japanese and non-Japanese automakers. There are no quantitatively meaningful responses of non-Japanese automakers in the months following March 2011.

5.1.4 Utilization of Inputs

Both of our strategies for inferring the elasticities of substitution between inputs require that some factor of production cannot be fully adjusted immediately after the shock. Consistent with this

²⁷These numbers are broadly similar, though somewhat lower than other estimates in the literature. See Ramey (1989) for one example.

assumption, we showed above that neither employment nor payroll responded significantly and argued that the predetermined capital stock has virtually no room to move in the short run (see Section 3.3). Here we extend this discussion and argue that variable factor utilization is also unlikely to pose a problem for our elasticity estimation.

Using data on employment and hours per worker from the Bureau of Labor Statistics we compute total hours in the manufacturing sector and in durable goods manufacturing. As shown in Appendix Figure B9, neither series displays a discernible drop after the shock. While the growth in these series slows down thereafter, it is clear that hours did not fall one-for-one with industrial production. We next re-estimated the model from Section 4, allowing for less than one-for-one changes in the utilization rate of capital and labor with output. We find that the estimates change very little. See Appendix B.6 and Table B1 for details.

5.1.5 Further Robustness

Finally, we conduct a series of additional robustness exercises. First, we weight firms by their relative size (North American exports in the period before the shock) and re-estimate the elasticities ζ and ω . The results, shown in Panel A of Table 5, are remarkably similar to our baseline estimates.²⁸ This evidence suggests that strong input complementarities are a key feature of firms' production functions regardless of their size.

Second, we ask whether our results are largely driven by the automotive industry. In the aftermath of the Tōhoku earthquake this sector was the focus of extensive news coverage emphasizing production disruptions due to parts shortages. We therefore re-estimate the parameters ζ and ω for the motor vehicle sector and its complement separately. The results are reported in Panel B of Table 5. Although sample sizes are small at this level of disaggregation, implying larger confidence intervals, we find that the low elasticity estimates are not driven exclusively by firms in the motor-vehicle sector. Unfortunately, the small sample size and U.S. Census Bureau disclosure requirements prevent us from estimating these elasticities industry-by-industry.

Third, Panel C of Table 5 shows that our results are robust to alternative parameter values for

²⁸The one exception is for the Non-Japanese multinationals, the confidence interval for the ω estimate increases from [0.16 0.69] to [0.30 1.23].

the capital share parameter (α , columns 1-2), the estimation window (3 month, column 3), and focusing exclusively on differentiated goods according to the Rauch (1999) classification (column 4).

5.1.6 The Product Composition of Imports

In the empirical analyses of Sections 3 and 4, we aggregate across products in our measurement of imported intermediates. Of course, an elasticity of substitution could be defined at many different levels of input aggregation. Our approach above seeks to balance the benefits of increased detail with measurement challenges that become more severe as the level of disaggregation rises. In Appendix B.10 we take one additional step and analyze the data at the product level. We construct a measure that captures compositional changes within Japanese imports of Japanese firms. There is no evidence for unusual changes in the product composition around the time of the Tōhoku event—which is consistent with firms changing the sourced quantities roughly in fixed proportion. However, we recognize that the data at the firm-product-month level are inherently noisy. This is also why we do not estimate elasticities at the product level. For further details, see Appendix B.10.

5.2 Implications and Discussion

In most IRBC models the cross-country correlation of GDP falls short of what it is in the data. We argue in this paper that part of this mismatch can be explained by input linkages with strong complementarities which are typically not included in these models. To quantify this effect we develop an IRBC model which we design and calibrate to match key aspects of the data (Boehm, Flaaen, and Pandalai-Nayar, 2014). Relative to earlier work our model differs in three dimensions. First and most importantly, the model features three types of firms: domestically producing firms, exporters, and multinational firms. As in the data, multinationals import intermediates from the source country. Motivated by the evidence in this paper they combine these intermediates with a capital/labor aggregate in fixed proportions. Second and consistent with firms' behavior after the Tōhoku disruption, all firms are subject to capital and labor adjustment costs. Third, we consider

short-lived shocks akin to the earthquake/tsunami. We find that relative to an alternative model without vertical linkages, GDP co-movement increases by 11 percentage points. As in earlier contributions, the main mechanism is that strong complementarities synchronize intermediate input demand across countries (Backus, Kehoe, and Kydland, 1994; Heathcote and Perri, 2002; Burstein, Kurz, and Tesar, 2008).²⁹

Our evidence for input complementarities has implications for the transmission of shocks through production networks more generally. In fact, when we re-estimate our dynamic treatment effects specification from Section 3.1 (equation 1) after replacing the left hand side with *non*-Japanese imports, we find that these imports also fell in response to the shock in Japan (see Appendix Figure B4). Consistent with our structural estimates, this implies a low aggregate elasticity between Japanese and non-Japanese trade. Moreover, it also implies that Non-Japanese upstream suppliers therefore suffered *indirectly* from the shock, via their exposure to firms with direct linkages to Japan. It is also likely that downstream suppliers that relied on inputs from the disrupted firms were also adversely affected. Quantitatively large upstream and downstream spillovers have been documented within Japan after the Tōhoku shock as well (Carvalho et al., 2014).

A body of theoretical work has demonstrated that production networks transmit and amplify shocks (e.g. Acemoglu et al., 2012). However, most of these models use production functions with a unit elasticity of substitution between inputs. Only a few papers focus on the role of input complementarities in propagating shocks through networks. These papers uniformly find that low values, similar to the structural estimates in this paper, best fit the empirical magnitudes of shock propagation. For instance, Barrot and Sauvagnat (2016) show that a calibrated network model delivers amplification of shocks closest to the data when the materials elasticity is near zero. At the sector-level, Atalay (2017) finds that augmenting input-output relationships with strong complementarities is critical for evaluating the contribution of industry-level shocks to aggregate fluctuations. His estimates of the sectoral input elasticity, which are perhaps the closest in spirit to

²⁹For additional work on the role of intermediate input trade and multinational firms in business cycle co-movement see Johnson (2014); Cravino and Levchenko (2017); Arkolakis and Ramanarayanan (2009); Menno (2016); Contessi (2015); Zlate (2016); de Soyres (2016).

those we estimate in this paper, are generally less than 0.2 and always less than 1, similar to our estimates.³⁰

Our findings also suggest that input linkages and complementarities increase volatility. These linkages played a critical role for the transmission of the Tōhoku shock from Japan to the U.S where manufacturing production fell by one percentage point. However, we note that theoretically the relationship between input linkages and volatility is ambiguous. A related literature which aims to explain the variation in cross-country output volatility argues that a greater variety of intermediates leads to less volatility (Koren and Tenreyro, 2013). In fact, Krishna and Levchenko (2014) demonstrate that even in the case of a Leontief production function, the volatility of output per worker can decrease in the number of intermediates used. On the other hand Kurz and Senses (2016) show that firm-level employment volatility is increasing in the share of imported intermediate inputs, as well as the number of import locations.

5.3 External Validity

As the variation we use to identify the production elasticities comes from one particular natural experiment, care must be taken when applying our results in alternative settings. As a first step, we examine whether input linkages of Japanese affiliates are unusual. As shown in Flaaen (2014), over 45 percent of the imports for all foreign multinational affiliates are sourced from the country of the parent firm. Although the cost share of imported intermediates from the source country is particularly high for Japanese multinationals, at 22 percent, the share from the source country for all foreign affiliates is still a substantial 12 percent. Finally, the cost share of all imported inputs in total inputs is 35 percent for Japanese affiliates and 32 percent for all foreign affiliates.

Second, it is likely that disruptions to trade linkages comprised primarily of homogeneous goods and commodities exhibit weaker downstream effects. Japan is somewhat special in that it exports a particularly high share of differentiated goods: roughly 97 percent of U.S. imports from Japan are in differentiated goods. On the other hand, 84 percent of U.S. imports from other countries are also differentiated goods, which is lower but nevertheless a sizable fraction.³¹ When

³⁰See also Foerster, Sarte, and Watson (2011); Bigio and La'O (2016); Baqaee (2016).

³¹This definition follows the “naive” categorization used in Bernard, Jensen, and Schott (2006): two-digit HS-

gauging the applicability of our estimates in other contexts, the share of differentiated products may be a useful metric.

Finally, there are more general considerations to take into account apart from the particular features of firms and products. As Ruhl (2008) emphasizes, the size of the appropriate elasticity is tied to the time horizon and the type of shock (temporary versus permanent). Larger values are applicable following permanent shocks, owing in part to adjustments along various extensive margins. We estimate the elasticity following a short-lived shock where the structure of the supply chain is plausibly fixed, i.e. firms do not instantly change their network of suppliers. We believe that our elasticity estimates apply when this criterion is roughly satisfied. Put differently, our estimates are most appropriately used after short-lived shocks or in the period of transition after long-lived but unexpected shocks.

Due to its short duration, the natural experiment used for identification in this paper does not permit the estimation of long-run elasticities. That said, we briefly discuss two extensions which are somewhat informative about the long run. First, Appendix B.11 discusses the extent of supplier switching following the Tōhoku event for Japanese affiliates. Such a shock could plausibly alter the network of suppliers and hence speak to longer-run considerations. However, we find no evidence of any significant supplier switching during this time period.

Second, we implement the methodology of Feenstra et al. (forthcoming) to contrast short and long run estimates. Based on an annual sample from 1994 to 2011 we estimate elasticities of substitution between HS10-level foreign varieties that are higher than ours and in line with those in their paper. Lengthening the time horizon to five years increases these estimates, but the differences are fairly small.³²

6 Conclusion

In this paper we showed that input linkages combined with strong complementarities are a key mechanism through which shocks are transmitted across borders. We used the Tōhoku earthquake

industries 01 to 21 and 25 to 29 are classified as commodities.

³²We would like to thank Philip Luck for helpful discussions and sharing their code. Note that the elasticities estimated here do not correspond to ω or ζ , but rather are similar to the elasticities in that paper.

and tsunami as an exogenous shock to demonstrate that firms that imported intermediates from Japan were unable to substitute to alternative inputs in the short run. As a result, these firms suffered large drops in U.S. production following the shock. We interpreted this behavior through the lens of a standard CES production function and concluded that the elasticity of substitution between alternate inputs is near zero in the short run. Structural estimation at the firm level confirmed this result.

The immediate sharp fall in production leaves little doubt that firm inventories played a very limited role after the Tōhoku shock. Given our findings of strong complementarities this result is somewhat surprising. Such complementarities should provide a significant incentive to hold inventories of intermediates. In light of its relevance for the literature on production networks and shock transmission, the size of inventory holdings and its determinants appear to be an important topic for further research.

Although it is well understood that domestic and foreign varieties are imperfectly substitutable (e.g. Goldberg et al., 2010), the degree of complementarity and its implications in the short run have received less attention. In this paper we argued that focusing on the short run is important. A short-lived shock in Japan had sizable effects in the United States, even in aggregate measures such as total manufacturing production. An open question is then to understand the time-frame over which adjustments to supply chains occur and whether such extensive margin changes can reconcile the small values of the elasticity that we find in the short run with larger estimates for the long run (e.g. Halpern, Koren, and Szeidl, 2015). Allowing for such extensive margin adjustments will allow for a more complete assessment of the contribution of input complementarities to business cycle fluctuations and the transmission of shocks through production networks.

References

- Acemoglu, Daron, Vasco M. Carvalho, Asuman Ozdaglar, and Alireza Tahbaz-Salehi. 2012. “The Network Origins of Aggregate Fluctuations.” *Econometrica* 80 (5):1977–2016.
- Arkolakis, Costas and Ananth Ramanarayanan. 2009. “Vertical Specialization and International Business Cycle Synchronization.” *Scandinavian Journal of Economics* 111 (4):655–680.
- Associated Press. 2011. “Quake to Force Shutdown of All US Toyota Plants.” April 5, 2011. <http://www.cbsnews.com/news/quake-to-force-shutdown-of-all-us-toyota-plants/> .
- Atalay, Englin. 2017. “How Important Are Sectoral Shocks?” *American Economic Journal: Macroeconomics* 9 (4):254–280.
- Backus, David K., Patrick J. Kehoe, and Finn E. Kydland. 1994. “Dynamics of the Trade Balance and the Terms of Trade: The J-Curve?” *American Economic Review* 84 (1):84–103.
- Baqae, David. 2016. “Cascading Failures in Production Networks.” Working Paper.
- Barrot, Jean-Noel and Julien Sauvagnat. 2016. “Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks.” *Quarterly Journal of Economics* 131 (3):1543–1592.
- Bernard, Andrew, J. Bradford Jensen, Stephen J. Redding, and Peter K. Schott. 2007. “Firms in International Trade.” *Journal of Economic Perspectives* 21 (3):105–130.
- Bernard, Andrew, J. Bradford Jensen, and Peter K. Schott. 2006. “Transfer Pricing by U.S.-Based Multinational Firms.” Working paper, Yale School of Management.
- Bigio, Saki and Jennifer La’O. 2016. “Financial Frictions in Production Networks.” Working Paper.
- Blasnik, Michael. 2010. “RECLINK: Stata module to probabilistically match records.”
- Bloom, Nicholas. 2009. “The Impact of Uncertainty Shocks.” *Econometrica* 77 (3):623–685.
- Boehm, Christoph, Aaron Flaaen, and Nitya Pandalai-Nayar. 2014. “Complementarities in Multi-national Production and Business Cycle Dynamics.” Working paper, University of Michigan.
- Burstein, Ariel, Christopher Kurz, and Linda Tesar. 2008. “International Trade, Production Sharing and the Transmission of Business Cycles.” *Journal of Monetary Economics* 44 (4):775–795.
- Busso, Matias, John DiNardo, and Justin McCrary. 2014. “New Evidence on the Finite Sample Properties of Propensity Score Reweighting and Matching Estimators.” *The Review of Economics and Statistics* 96 (5):885–897.
- Carvalho, V., M. Nirei, Y.U. Saito, and A. Tahbaz-Salehi. 2014. “Supply Chain Disruptions: Evidence from the Great East Japan Earthquake.” Working Paper.

- Carvalho, Vasco and Xavier Gabaix. 2013. “The Great Diversification and Its Undoing.” *American Economic Review* 103 (5):1697–1727.
- Contessi, Silvio. 2015. “Multinational Firms’ Entry and Productivity: Some Aggregate Implications of Firm-level Heterogeneity.” Globalization and Monetary Policy Institute Working Paper, Federal Reserve Bank of Dallas.
- Cox, Jeff. 2011. “U.S. Economy Damaged More Than Thought by Japan Quake.” May 25, 2011. <http://www.cnbc.com/id/43169530> .
- Cravino, Javier and Andrei Levchenko. 2017. “Multinational Firms and International Business Cycle Transmission.” *Quarterly Journal of Economics* 132 (2):921–962.
- de Soyres, Francois. 2016. “Value Added and Productivity Linkages Across Countries.” Working Paper.
- di Giovanni, Julian and Andrei Levchenko. 2010. “Putting the Parts Together: Trade, Vertical Linkages, and Business Cycle Comovement.” *American Economic Journal: Macroeconomics* 1 (1):95–124.
- di Giovanni, Julian, Andrei A. Levchenko, and Isabelle Mejean. 2014. “Firms, Destinations, and Aggregate Fluctuations.” *Econometrica* 82 (4):1303–1340.
- Feenstra, Robert C., Philip A. Luck, Maurice Obstfeld, and Katheryn N. Russ. forthcoming. “In Search of the Armington Elasticity.” *The Review of Economics and Statistics* .
- Flaaen, Aaron. 2013. “Constructing a Bridge Between the LexisNexis Directory of Corporate Affiliations and the U.S. Business Register.” Working paper, University of Michigan.
- . 2014. “Multinational Firms in Context.” Working paper, University of Michigan.
- Foerster, Andrew T., Pierre-Daniel G. Sarte, and Mark W. Watson. 2011. “Sectoral versus Aggregate Shocks: A Structural Factor Analysis of Industrial Production.” *Journal of Political Economy* 119 (1):1 – 38.
- Frankel, Jeffrey A. and Andrew K. Rose. 1998. “The Endogeneity of the Optimum Currency Area Criteria.” *Economic Journal* 108 (449):1009–1025.
- Gabaix, Xavier. 2011. “The Granular Origins of Aggregate Fluctuations.” *Econometrica* 79:733–772.
- Goldberg, Penelope, Amit Kumar Khandelwal, Nina Pavcnik, and Petia Topalova. 2010. “Imported Intermediate Inputs and Domestic Product Growth: Evidence from India.” *Quarterly Journal of Economics* 125 (4):1727–1767.
- Halpern, László, Miklós Koren, and Adam Szeidl. 2015. “Imported Inputs and Productivity.” *American Economic Review* 105 (12):3660–3703.

- Heathcote, Jonathan and Fabrizio Perri. 2002. "Financial Autarky and International Business Cycles." *Journal of Monetary Economics* 49:601–627.
- Hirschmann, A.O. 1958. "Interdependence and Industrialization." In *The Strategy of Economic Development*. New Haven: Yale University Press.
- House, Christopher L. and Matthew D. Shapiro. 2008. "Temporary Investment Tax Incentives: Theory with Evidence from Bonus Depreciation." *American Economic Review* 98 (3):737–68.
- Imbs, Jean. 2004. "Trade, Finance, Specialization, and Synchronization." *Review of Economics and Statistics* 86 (3):723–734.
- Jarmin, Ron and Javier Miranda. 2002. "The Longitudinal Business Database." Mimeo, available at <http://www.vrdc.cornell.edu/info7470/2007/Readings/jarmin-miranda-2002.pdf>.
- Johnson, Robert C. 2014. "Trade in Intermediate Inputs and Business Cycle Comovement." *American Economic Journal: Macroeconomics* 6 (4):39–83.
- Johnson, Robert C. and Guillermo Noguera. 2012. "Accounting for Intermediates: Production Sharing and Trade in Value Added." *Journal of International Economics* 86 (2):224–236.
- Jones, Charles I. 2011. "Intermediate Goods and Weak Links in the Theory of Economic Development." *American Economic Journal: Macroeconomics* 3 (2):1–28.
- Koren, Miklós and Silvana Tenreyro. 2013. "Technological Diversification." *American Economic Review* 103 (1):378–414.
- Kremer, Michael. 1993. "The O-Ring Theory of Economic Development." *Quarterly Journal of Economics* 108 (3):551–575.
- Krishna, Pravin and Andrei Levchenko. 2014. "Comparative Advantage, Complexity, and Volatility." *Journal of Economic Behavior and Organization* 94:314–329.
- Kurz, Christopher Johann and Mine Zeynep Senses. 2016. "Importing, Exporting and Firm-Level Employment Volatility." *Journal of International Economics* 98:160–175.
- Leontief, Wassily. 1936. "Quantitative Input and Output Relations in the Economic Systems of the United States." *The Review of Economics and Statistics* 18 (3):105–125.
- Menno, Dominik. 2016. "Multinational Firms and Business Cycle Transmission." Working Paper.
- Pierce, Justin and Peter Schott. 2012. "A Concordance Between U.S. Harmonized System Codes and SIC/NAICS Product Classes and Industries." *Journal of Economic and Social Measurement* 37 (1-2):61–96.
- Ramey, Valerie A. 1989. "Inventories as Factors of Production and Economic Fluctuations." *American Economic Review* 79 (3):338–354.

- Rauch, James E. 1999. “Networks Versus Markets in International Trade.” *Journal of International Economics* 48:7–35.
- Ruhl, Kim J. 2008. “The International Elasticity Puzzle.” Working paper, NYU Stern School of Business.
- Schnell, Molly and David E. Weinstein. 2012. “Evaluating the Economic Response to Japan’s Earthquake.” Working Paper 12-P-003, RIETI.
- The Economist Intelligence Unit. 2009. “Managing Supply-Chain Risk for Reward.” Tech. rep., The Economist.
- Wald, Davis J, Bruce C. Worden, Vincent Quitoriano, and Kris L. Pankow. 2006. “ShakeMap Manual: Technical Manual, User’s Guide and Software Guide.” Tech. rep., U.S. Geological Survey. URL <http://pubs.usgs.gov/tm/2005/12A01/>.
- Wasi, Nada and Aaron Flaaen. 2015. “Record linkage using Stata: Preprocessing, linking, and reviewing utilities.” *Stata Journal* 15 (3):672–697(26).
- Zlate, Andrei. 2016. “Offshore Production and Business Cycle Dynamics with Heterogeneous Firms.” *Journal of International Economics* 100 (C):34–49.

Table 1: Summary Statistics

<i>Panel A: Cost Share Of Imported Inputs</i>					
	Japanese Firms	Non Multinationals			
from Japan	21.8	1.0			
from all countries	35.0	17.5			
<i>Panel B: Treatment Effects Sample Details</i>					
	Japanese Firms	Other Multinationals	Balancing Tests <i>t</i>	<i>p</i> -value	% bias Reduction
N.A. Exports share intra-firm	3,504,894 72.0	3,413,058 52.2	0.38	0.706	79.1
Intermediate Input Imports	8,075,893	7,596,761	0.87	0.384	88
of which: share from Japan	70.0	3.5			
of which: share intra-firm	86.0	21.7			
Industry (arithmetic mean) [†]	–	–	–	0.965	97.8

Notes: Panel A data are for year 2007. Panel B reports the baseline average values of N.A. exports and intermediate input imports, as well as the characteristics of that trade, for the two groups of firms: Japanese affiliates and other multinational firms. The statistics are calculated in the three months prior to the Tōhoku earthquake: December 2010, January 2011, and February 2011. The control group of other multinational firms has been re-weighted using the normalized propensity score, which we constructed from a specification including the level of N.A. exports, intermediate input imports, and industry dummies. The final three columns report balancing tests of the equality of the means between the treated and control group. Sources: LFTTD, DCA, and UBP as explained in the text.

[†]Due to disclosure requirements we were not able to disclose the test results for individual industries (including quantiles). The reported values are therefore arithmetic means.

Table 2: Dynamic Treatment Effects: Unit Values of Trade Around the Tōhoku Event

Independent Variables	Log Unit-Value of:			
	JPN Imports: Related Party (1)	JPN Imports: Non-Related Party (2)	N.A. Exports Related Party (3)	N.A. Exports Non-Related Party (4)
JPNxSep 2010 (t=-6)	-0.0175 (0.0162)	-0.00790 (0.0274)	-0.0453 (0.0363)	-0.0379 (0.0303)
JPNxOct 2010 (t=-5)	-0.0257 (0.0167)	-0.00682 (0.0282)	0.0002 (0.0383)	-0.0278 (0.0288)
JPNxNov 2010 (t=-4)	-0.00548 (0.0164)	0.0824** (0.0274)	-0.0570 (0.0351)	-0.0715** (0.0309)
JPNxDec 2010 (t=-3)	-0.0232 (0.0151)	-0.0202 (0.0270)	-0.0407 (0.0373)	-0.0417 (0.0328)
JPNxJan 2011 (t=-2)	0.0216 (0.0172)	0.0748** (0.0279)	-0.0052 (0.0392)	-0.0719** (0.0289)
JPNxFeb 2011 (t=-1)	0.0278 (0.0162)	0.00642 (0.0279)	0.0222 (0.0409)	-0.0288 (0.0322)
JPNxMar 2011 (t=0)	0.0100 (0.0164)	0.00413 (0.0272)	0.0155 (0.0351)	0.0004 (0.0303)
JPNxApr 2011 (t=1)	0.00475 (0.0173)	0.0162 (0.0296)	0.0175 (0.0369)	-0.0222 (0.034)
JPNxMay 2011 (t=2)	0.00407 (0.0174)	0.0640 (0.0308)	-0.0079 (0.039)	-0.0244 (0.0327)
JPNxJun 2011 (t=3)	0.0117 (0.0174)	-0.00499 (0.0289)	0.0077 (0.0401)	-0.0918*** (0.0311)
JPNxJul 2011 (t=4)	0.00114 (0.0183)	0.0350 (0.0304)	0.0232 (0.0409)	-0.0217 (0.0296)
JPNxAug 2011 (t=5)	-0.0141 (0.0176)	-0.0165 (0.0302)	0.0052 (0.0375)	-0.0368 (0.0297)
JPNxSep 2011 (t=6)	-0.00740 (0.0178)	0.0366 (0.0306)	-0.0288 (0.0358)	-0.0155 (0.0332)
JPNxOct 2011 (t=7)	0.0169 (0.0182)	0.0221 (0.0303)	-0.0209 (0.0392)	-0.0545 (0.0304)
JPNxNov 2011 (t=8)	0.0278 (0.0183)	0.0620** (0.0287)	-0.0149 (0.0362)	-0.0365 (0.0335)
JPNxDec 2011 (t=9)	0.0194 (0.0178)	0.0503 (0.0313)	-0.0037 (0.0392)	-0.0241 (0.0334)
Constant	4.257 (0.00284)	3.857 (0.00261)	3.35 (0.0041)	3.600 (0.0032)
Month Fixed Effects	Yes	Yes	Yes	Yes
Firm-product Fixed Effects	Yes	Yes	Yes	Yes
Observations	1,198,000	1,568,000	522,000	603,000
R ²	0.939	0.935	0.944	0.955

Notes: Significance levels based on robust standard errors (clustered at the firm-product level) are indicated by: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. This table reports features of the unit values of trade around the 2011 Tōhoku earthquake and tsunami. The first set of coefficients correspond to monthly dummies, whereas the second set (JPNx) correspond to the interaction of a Japanese firm dummy with monthly dummies. See equation (2) in the text. Sources: LFTTD, DCA, and UBP as explained in the text.

Table 3: Dynamic Treatment Effects: Quarterly Employment/Payroll

Independent Variables	Log 4-Quarter Difference	
	Employment (1)	Payroll (2)
JPNxQ2_2010 (t=-3)	0.0116 (0.0124)	0.0154 (0.0143)
JPNxQ3_2010 (t=-2)	0.0026 (0.0151)	0.0016 (0.0145)
JPNxQ4_2010 (t=-1)	0.0043 (0.019)	-0.0129 (0.0173)
JPNxQ1_2011 (t=0)	0.0121 (0.0201)	0.0048 (0.0256)
JPNxQ2_2011 (t=1)	-0.0103 (0.0196)	-0.0116 (0.0235)
JPNxQ3_2011 (t=2)	-0.0289 (0.0268)	0.0014 (0.0233)
JPNxQ4_2011 (t=3)	-0.0048 (0.0224)	0.0219 (0.0221)
Constant	-0.0572 (0.0051)	-0.0492 (0.0057)
Quarter Fixed Effects	Yes	Yes
Firm Fixed Effects	Yes	Yes
Observations	21,500	21,500
R ²	0.381	0.388

Notes: Significance levels based on robust standard errors (clustered at the firm-level) are indicated by: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. This table reports features of firm employment and firm payroll in the quarters around the Tōhoku earthquake and tsunami. The first set of coefficients correspond to quarter dummies, whereas the second set (JPNx) correspond to the interaction of a Japanese firm dummy with quarter dummies. See equation (B1) in the text. The dependent variable is the four-quarter log difference of employment (payroll). Sources: SSEL and DCA as explained in the text.

Table 4: Firm-Level Estimation: Results and Sample Details

Panel A: Calibration				
Parameter	Value			
R_t	0.07			
α	1/3			
Panel B: Estimation Results				
	Japanese Multinationals	Non-Japanese Multinationals	Non- Multinationals	All Firms
ω	0.201 [0.02 0.43]	0.624 [0.16 0.69]	0.423 [0.26 0.58]	0.552 [0.21 0.62]
ζ	0.032 [0.030 0.673]	0.038 [0.035 0.508]	0.032 [0.029 1.68]	0.037 [0.034 0.038]
Sample Details				
Avg. Weight on K/L Aggregate ($\bar{\mu}$)	0.223	0.514	0.278	0.409
Avg. Weight on JPN Materials ($1 - \bar{\nu}$)	0.173	0.044	0.147	0.096
Number of Firms	105	304	141	550
Share of Total Trade				
JPN int imports	0.60	0.23	0.03	0.86
Non-JPN int imports	0.02	0.66	0.01	0.69
N.A. exports	0.08	0.47	0.01	0.56

Notes: This table reports the results from the firm-level estimation detailed in section 4. Panel A outlines the parameters that are calibrated prior to estimation. The top two rows of Panel B reports the point estimates of the elasticities, and the corresponding 95 percent bootstrapped confidence intervals (See Appendix B.7 for more details). Rows 3 and 4 report other estimates related to the calculated production functions. The final rows of Panel B describe features of the estimation samples. Sources: CM, LFTTD, DCA, and UBP as explained in the text.

Table 5: Firm-Level Estimation: Robustness

Panel A: Estimation Results (Weighted)				
	Japanese Multinationals	Non-Japanese Multinationals	Non- Multinationals	All Firms
ω	0.157 [0.02 0.40]	0.611 [0.30 1.23]	0.543 [0.305 0.57]	0.606 [0.28 0.70]
ζ	0.241 [0.03 0.884]	0.038 [0.034 0.51]	0.032 [0.029 0.55]	0.037 [0.034 0.038]
Number of Firms	105	304	141	550
Panel B: Estimation Results: Motor Vehicle Sector				
	Japanese Multinationals		All Firms	
	Motor Vehicles	Non-Motor Vehicles	Motor Vehicles	Non-Motor Vehicles
ω	0.311 [0.019 0.398]	0.094 [0.016 0.59]	0.414 [0.27 0.60]	0.574 [0.16 0.66]
ζ	0.032 [0.030 0.48]	0.071 [0.028 1.27]	0.037 [0.031 0.64]	0.037 [0.033 0.037]
Number of Firms	35	70	100	450
Panel C: Other Robustness: All Firms Sample				
	Varying Capital Share (α)		3-month Window	Differentiated Goods
	$\alpha = 0.2$	$\alpha = 0.5$		
ω	0.519 [0.41 1.32]	0.423 [0.292 0.713]	0.555 [0.285 1.745]	0.540 [0.355 1.233]
ζ	0.037 [0.035 0.038]	0.038 [0.036 0.65]	0.038 [0.035 0.039]	0.038 [0.035 0.038]
Sample:	All Firms (compare to Column 4 of Table 4)			

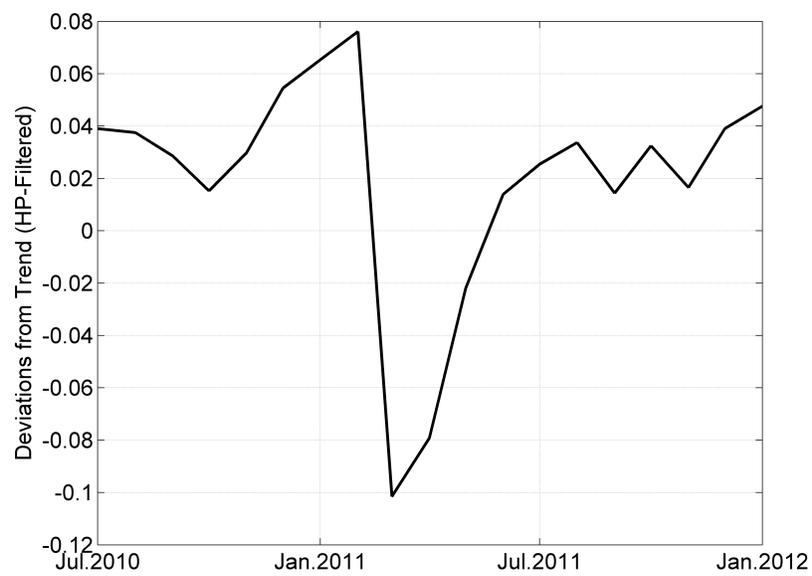
Notes: The table reports additional estimation results. Panel A recalculates the results from Table 4 after weighting firms by their relative size (North American exports). Panel B divides the samples based on the motor vehicle industry. Sources: CM, LFTTD, DCA, and UBP as explained in the text. Panel C varies the calibration parameters and estimation window. Panels A and B use the same calibration parameters as Table 4.

Table 6: Summary Statistics: Inventories by Firm Type

	Japanese Multinationals	Non Multinationals
Inputs	0.83	1.08
Output	0.31	0.45

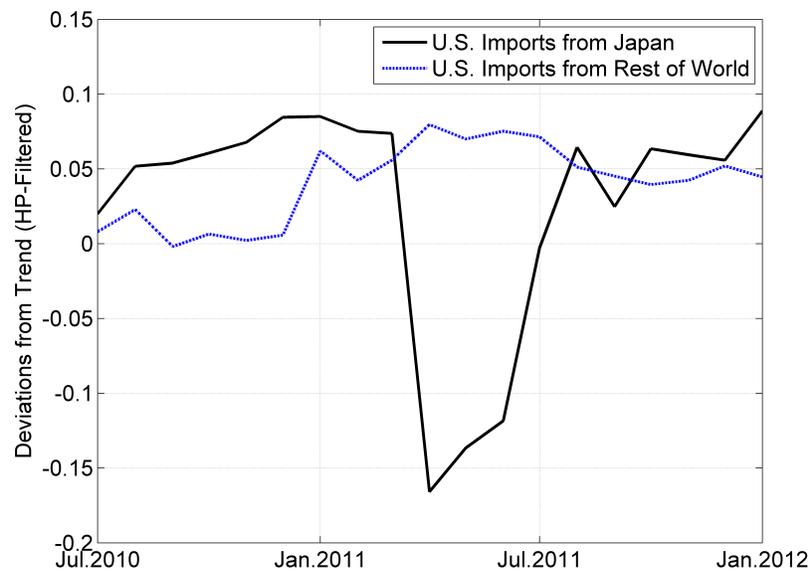
Notes: The table reports the months' supply of inventories [beginning period inventory stock/(usage/12)] for materials and output for the Census year 2007. Sources: CM, LFTTD, DCA, and UBP as explained in the text.

Figure 1: Index of Japanese Industrial Production: Manufacturing



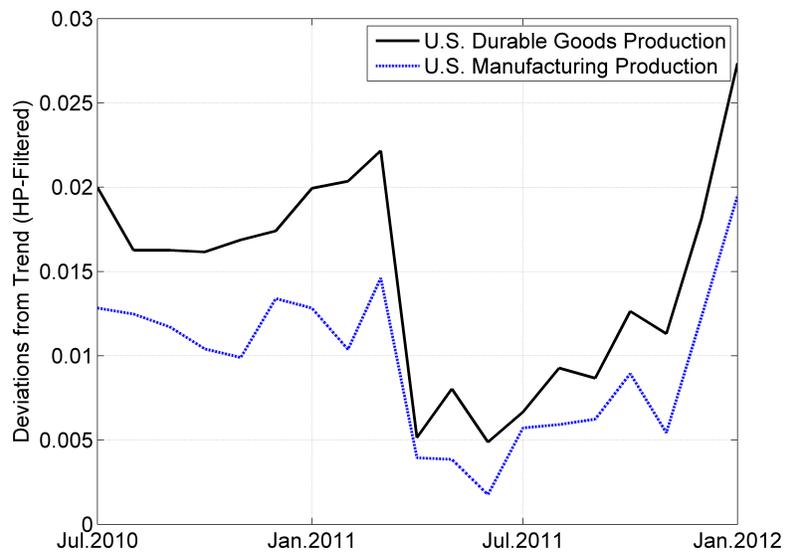
Notes: The series shown is seasonally adjusted, logged and detrended. We use an HP filter with a smoothing parameter of 14400. Source: Japanese Ministry of Economy, Trade, and Industry (METI).

Figure 2: U.S. Imports from Japan and Rest of World



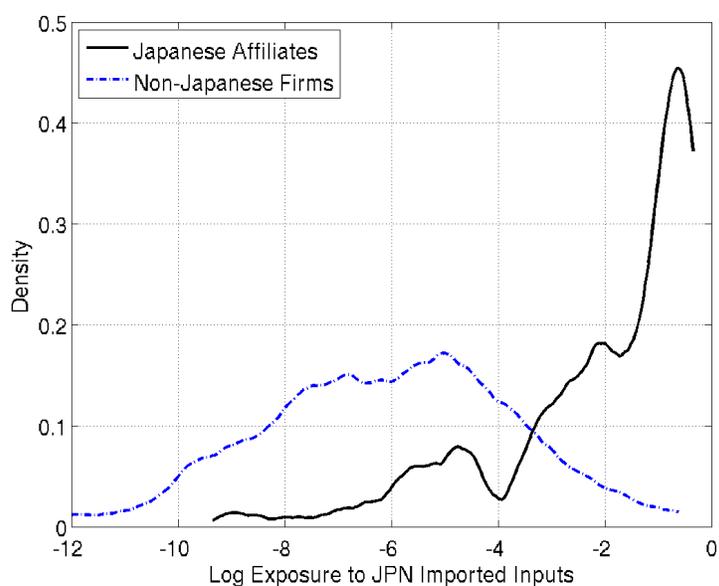
Notes: The series are in constant prices, seasonally adjusted, logged and detrended. We use an HP filter with a smoothing parameter of 14400.
Source: U.S. Census Bureau, based on published totals.

Figure 3: U.S. Industrial Production: Manufacturing and Durable Goods



Notes: The series shown are seasonally adjusted, logged and detrended. We use an HP filter with a smoothing parameter of 14400. Source: Federal Reserve Board.

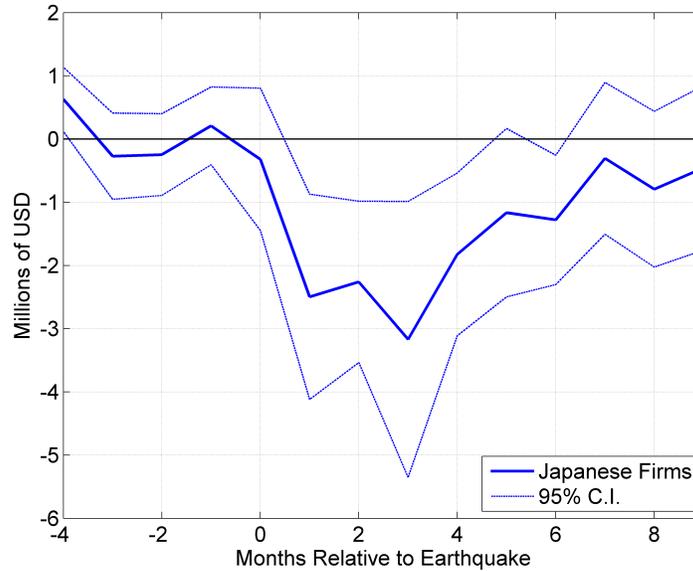
Figure 4: Density of Firm-Level Exposure to Japanese Imported Inputs: By Firm Type



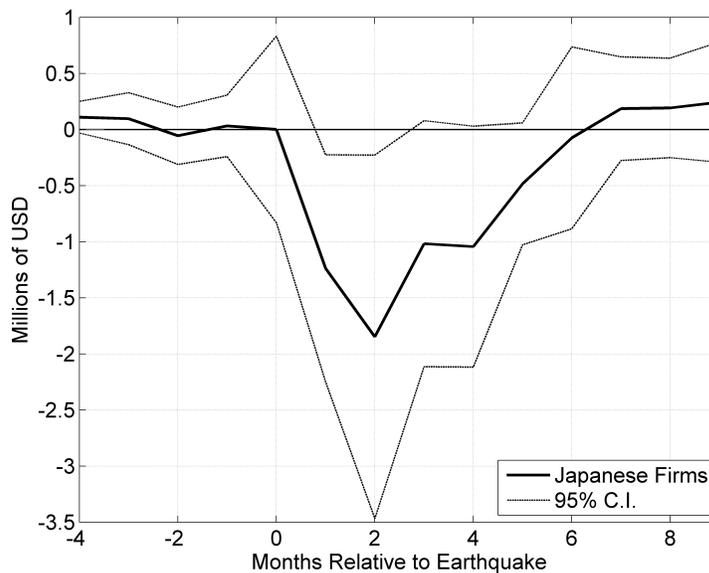
Notes: This figure displays density estimates of the log exposure measure to Japanese imported inputs, separately for Japanese affiliates and non-Japanese multinational firms for the year 2010. The measure is defined as the ratio of Japanese imported inputs to total imported inputs plus U.S. salaries and wages. Estimates at either tail are suppressed to comply with U.S. Census Bureau disclosure requirements. Sources: LFTTD, DCA, and UBP as explained in text.

Figure 5: Dynamic Treatment Effects: Japanese Firms

A. Relative Intermediate Input Imports of Japanese Firms

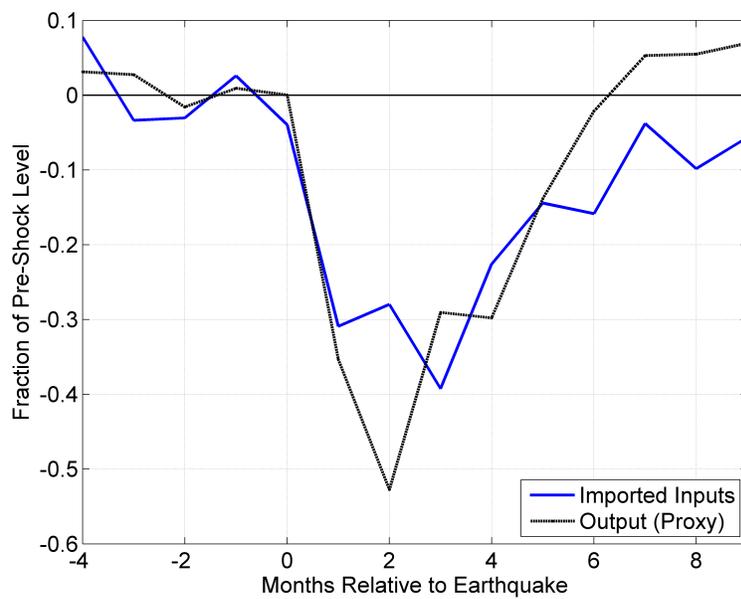


B. Relative North American Exports of Japanese Firms



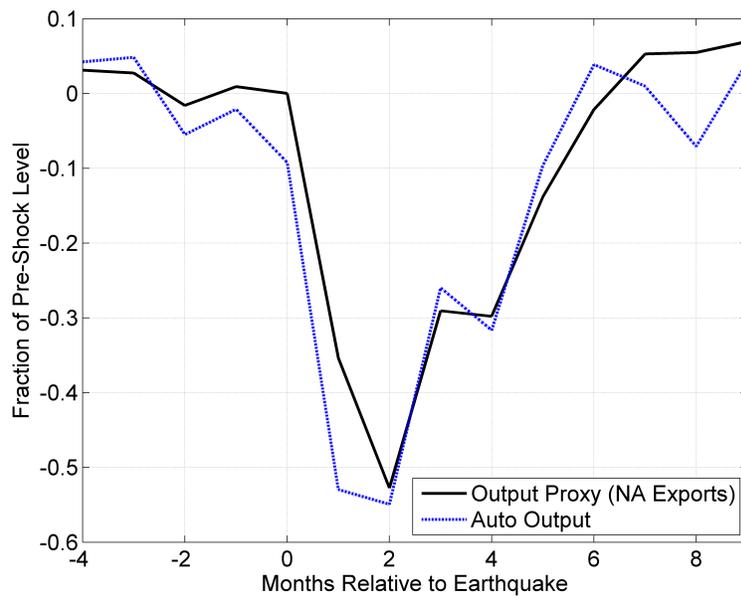
Notes: The figure reports the intermediate imports and North American exports of the U.S. affiliates of Japanese firms relative to a control group of other multinational firms. The values are coefficient estimates taken from an interaction of a Japanese-firm dummy with a month dummy. See equation (1) in the text. Standard errors are clustered at the firm level. Sources: LFTTD, DCA, and UBP as explained in text.

Figure 6: Relative Imported Inputs and Output (Proxy) of Japanese Firms: Fraction of Pre-Shock Level



Notes: The figure reports the intermediate imports and output proxy (North American exports) of the U.S. affiliates of Japanese firms relative to a control group of other multinational firms. The values are percent changes from the pre-shock level of each series, defined as the average of the months December 2010, January 2011, and February 2011. Sources: LFTTD, DCA, and UBP as explained in text.

Figure 7: Assessing the Output Proxy Using Monthly Automotive Production



Notes: The figure reports production of Japanese automakers relative to non-Japanese automakers together with the production proxy (North American exports, see Figure 6). The Japanese automakers are Honda, Isuzu, Mazda, Mitsubishi, Nissan, Toyota, and Subaru. The auto series is constructed by first summing the seasonally adjusted counts of cars and trucks produced, separately for all Japanese and non-Japanese manufacturers. These two series are then detrended using the HP filter with smoothing parameter 14400. We then take the difference between the series for Japanese and non-Japanese automakers. See Appendix B.9 for more details. Source: Ward's Automotive Database.

A Data Appendix

A.1 Matching Corporate Directories to the Business Register

The discussion below is an abbreviated form of the full technical note (see Flaaen, 2013) documenting the bridge between the Directory of Corporate Affiliations and the Business Register.

A.1.1 Directories of International Corporate Structure

The LexisNexis Directory of Corporate Affiliations (DCA) is our primary source of information on the ownership and locations of U.S. and foreign multinational affiliates. The DCA describes the organization and hierarchy of public and private firms, and consists of three separate databases: U.S. Public Companies, U.S. Private Companies, and International (parent companies with headquarters located outside the United States). The U.S. Public database contains all firms traded on the largest U.S. exchanges, as well as major firms traded on smaller U.S. exchanges. Firms in the U.S. Private database must have revenues in excess of \$1 million, 300 or more employees, or substantial assets. Firms in the International database, which includes both public and private companies, generally have revenues greater than \$10 million. Each database contains information on all subsidiaries, regardless of location.

The second source used to identify multinational firms comes from Uniworld Business Publications (UBP). This company has produced periodic volumes documenting the locations and international scope of i) American firms operating in foreign countries; and ii) foreign firms with operations in the United States. Although only published biennially, the benefit of using these directories is their focus on multinational firms and the lack of a sales threshold for inclusion.

As no common identifiers exist between these directories and Census Bureau data infrastructure, we rely on probabilistic name and address matching—otherwise known as “fuzzy merging”—to link the directories to the Census data infrastructure.

A.1.2 Background on Name and Address Matching

Matching two data records based on name and address information is necessarily an imperfect exercise. Issues such as abbreviations, misspellings, alternate spellings, and varied name conventions rule out an exact merging procedure. This leaves probabilistic string matching algorithms that evaluate the “closeness” of match—given by a score or rank—between any two character strings in question. Due to the large computing requirements of these algorithms, it is common to use “blocker” variables to restrict the search samples within each dataset. The “blocker” variables must match exactly between the two datasets. For name and address matching, the most common “blocker” variables are the state and city of the establishment.

The matching procedure uses a set of record linking utilities described in Wasi and Flaaen (2015). This program uses a bigram string comparator algorithm on multiple variables with differing user-specified weights.³³ This way the researcher can apply, for example, a larger weight on a

³³The term bigram refers to two consecutive characters within a string (the word *bigram* contains 5 possible bigrams: “bi”, “ig”, “gr”, “ra”, and “am”). The program is a modified version of an existing string comparator algorithm

near *name* match than on a perfect *zip code* match. Hence, the “match score” for this program is a weighted average of each variable’s percentage of bigram character matches.

A.1.3 The Unit of Matching

The primary unit of observation in the DCA, UBP, and BR datasets is the business establishment. Hence, the primary unit of matching is the establishment, and not the firm. There are a number of important challenges with an establishment-to-establishment link. First, the DCA (UBP) and BR may occasionally have differing definitions of the establishment. One dataset may separate out several operating groups within the same firm address (i.e. JP Morgan – Derivatives, and JP Morgan – Emerging Markets), while another may group these activities together by their common address. Second, the name associated with a particular establishment can at times reflect the subsidiary name, location, or activity (i.e. Alabama plant, processing division, etc.), and at times reflect the parent company name. Recognizing these challenges, the primary goal of the matching is to assign each DCA (UBP) establishment to the most appropriate business location of the parent firm identified in the BR. As such, the primary matching variables are the establishment name, along with geographic indicators of street, city, zip code, and state.

A.1.4 The Matching Process: An Overview

The danger associated with probabilistic name and address matching is the potential for false-positive matches. Thus, there is an inherent tension for the researcher between broad search criteria that seek to maximize the number of matches and narrow and exacting criteria that eliminate false-positive matches. The matching approach used here is conservative in the sense that the methodology will favor criteria that limit false positives, at the expense of slightly lower match rates. The procedure generally requires a match score exceeding 95 percent, except in those cases where ancillary evidence provides increased confidence in the match.³⁴

This matching proceeds in an iterative fashion, in which a series of matching procedures are applied with decreasingly restrictive sets of matching requirements. In other words, the initial matching attempt uses the most stringent standards possible, after which the non-matching records move to a further matching iteration, with slightly less stringent standards. In each iteration, the matched records are assigned a flag that indicates the standard associated with the match.

See Table A1 for a summary of the establishment-level match rate statistics by year and type of firm, when using the DCA data. Table A2 lists the corresponding information for the Uniworld data.

by Blasnik (2010), and assigns a score for each variable between the two datasets based on the percentage of matching bigrams. See Flaaen (2013) or Wasi and Flaaen (2015) for more information.

³⁴The primary sources of such ancillary evidence are clerical review of the matches, and additional parent identifier matching evidence.

A.1.5 Construction of Multinational Indicators

The DCA data allows for the construction of variables indicating the multinational status of the U.S.-based establishment. If the parent firm contains addresses outside of the United States, but is headquartered within the U.S., we designate this establishment as part of a U.S. multinational firm. If the parent firm is headquartered outside of the United States, we designate this establishment as part of a Foreign multinational firm. We also retain the nationality of Foreign parent firm.³⁵

A number of issues arise when using the DCA-based indicators through the DCA-BR bridge within the Census Bureau data architecture. First, there may be disagreements between the DCA and Census on the boundaries of a firm. Establishment matches may report differing DCA-based multinational parent indicators for the same Census-identified firm. Second, a classification issue might also arise due to joint-ventures. Finally, incorrect establishment-level matches may also affect the definition of a multinational *firm*. To address these issues, we apply the following rules when using the DCA-based multinational indicators and aggregating to the (Census-based) firm level. There are three potential cases:³⁶

Potential case 1: A Census-identified firm in which two or more establishments match to different foreign-country parent firms

1. Collapse the Census-identified firm's employment into shares based on the establishment-parent firm link by country of foreign ownership
2. Calculate the firm employment share of each establishment match
3. If one particular link to a country of foreign ownership yields an employment share above 0.75, apply that link to all establishments within the firm.
4. If one particular link to a country of foreign ownership yields an employment share above 0.5 and total firm employment is below 10,000, then apply that link to all establishments within the firm.
5. All other cases require manual review.

Potential Case 2: A Census-identified firm in which one establishment is matched to a foreign-country parent firm, and another establishment is matched to a U.S. multinational firm.

1. Collapse the Census-identified firm employment into shares based on the establishment-parent firm link by type of DCA link (Foreign vs U.S. multinational)
2. Calculate the firm employment share of each establishment match
3. If one particular type of link yields an employment share above 0.75, apply that link to all establishments within the firm.

³⁵The multinational status of firms from the UBP directories are more straightforward, as these publications only list multinational firms.

³⁶Some of these cases also apply to the UBP-BR bridge.

4. If one particular type of link yields an employment share above 0.5 and total firm employment is below 10,000, then apply that link to all establishments within the firm.
5. All other cases require manual review.

Potential Case 3: A Census-identified firm in which one establishment is matched to a non-multinational firm, and another establishment is matched to a foreign-country parent firm (or U.S. multinational firm).

Apply same steps as in Potential Case 2.

A.2 Classifying Firm-Level Trade into intermediates and final goods

The firm-level data on imports available in the LFTTD do not contain information on the intended use of the goods. Fortunately, the Census Bureau data contains other information that can be used to distinguish intermediate input imports from final goods imports. Creating lists of the principal products produced by firms in a given detailed industry in the United States should indicate the types of products that, when imported, should be classified as a “final” good—that is, intended for final sale without further processing by the firm. The products imported outside of this set can then be classified as intermediate goods.³⁷ Such product-level production data exists as part of the “Products” trailer file of the Census of Manufacturers. As noted in Pierce and Schott (2012, p. 11), ours is one of many applications where merging product-level data on production, exports, and imports is critical.

A.2.1 Creating a NAICS-Based set of Final/Intermediate Products

As part of the quinquennial Census of Manufacturers (CM), the Census Bureau surveys establishments on their total shipments broken down into a set of NAICS-based (6 digit) product categories. Each establishment is given a form—specific to its industry—with a list of pre-specified products. There is also additional space to record other product shipments not included in the form. The resulting product trailer file to the CM allows the researcher to understand the principal products produced at each manufacturing establishment during a census year.

There are several data issues that must be addressed before using the CM-Products file to infer information about the relative value of product-level shipments by a particular firm. First, the trailer file contains product codes that are used to “balance” the aggregated product-level value of shipments with the total value of shipments reported on the base CM survey form. We drop these product codes from the dataset. Second, there are often codes that do not correspond to any official 7-digit product code identified by Census. (These are typically products that are self-identified by the firm but do not match any of the pre-specified products identified for that industry by Census.) Rather than ignoring the value of shipments corresponding to these codes, we attempt to match at a more aggregated level. We iteratively try to find a product code match at the 6, 5, and 4 digit product code level, and use the existing set of 7-digit matches as weights to allocate the product value among the 7-digit product codes encompassed by the more aggregated level.

³⁷To be more precise, this set will include a combination of intermediate and capital goods.

We now discuss how this file can be used to assemble a set of NAICS product codes that are the predominant output (final goods) for a given NAICS industry. Let x_{pij} denote the value of shipments of product p by establishment i in industry j during a census year. Then the total value of output of product p in industry j can be written as:

$$X_{pj} = \sum_{i=1}^{I_j} x_{pij},$$

where I_j is the number of firms in industry j . Total output of industry j is then:

$$X_j = \sum_{p=1}^{P_j} X_{pj}.$$

The share of industry output accounted for by a given product p is therefore:

$$S_{pj} = \frac{X_{pj}}{X_j}.$$

One might argue that the set of final goods products for a given industry should be defined as the set of products where $S_{pj} > 0$. That is, a product is designated as a “final good” for that industry if *any establishment* recorded positive shipments of the product. The obvious disadvantage of employing such a zero threshold is that small degrees of within-industry heterogeneity will have a disproportional effect on the classification.

In light of this concern, we set a threshold level W such that a product p in industry j with $S_{pj} > W$ is classified as a final good product for that industry. The upper portion of Table A3 documents the number of final goods products and the share of intermediate input imports based on several candidate threshold levels. The issues of a zero threshold are quite clear in the table; a small but positive threshold value (0.1) will have a large effect on the number of products designated as final goods. This shows indirectly that there are a large number of products produced by establishments in a given industry, but a much smaller group that comprise the bulk of total value.

There are several advantages to using the CM-Products file rather than using an input-output table.³⁸ First, within a given CM year, the classification can be done at the firm or establishment level rather than aggregating to a particular industry. This reflects the fact that the same imported product may be used as an input by one firm and sold to consumers as a final product by another. Second, the CM-Products file is one of the principal data inputs into making the input-output tables, and thus represents more finely detailed information. Third, the input-output tables for the U.S. are based on BEA industry classifications, which imply an additional concordance (see below) to map them into the NAICS-based industries present in the Census data. We next describe the procedure that uses these industry-level product classifications to map firm-level trade into intermediate and

³⁸Another option is to use the CM-Materials file, the flip side of the CM-Products file. Unfortunately, the CM-Materials file contains significantly more problematic product codes than the Products file, and so concurring to the trade data is considerably more difficult.

final goods.

A.2.2 Mapping HS Trade Transactions to the Product Classification

The LFTTD classifies products according to the U.S. Harmonized Codes (HS), which must be mapped to the NAICS-based product system in order to utilize the classification scheme from the CM-Products file. We use the concordance created by Pierce and Schott (2012) to map the firm-HS codes present in the LFTTD data to the firm-NAICS product codes present in the CM-Products data.

A challenge of this strategy is that the LFTTD exists at a firm-level, while the most natural construction of the industry-level classification scheme is by establishment. More concretely, for multi-unit, multi-industry firms, the LFTTD cannot be used to decompose an import shipment into the precise establishment-industry of its U.S. destination. We adopt the approach that is commonly used in these circumstances to deal with this issue. The industry of the firm is defined as that industry encompassing the largest employment share of its establishments.

Once the firm-level trade data is in the same product classification as the industry-level filter created from the CM-Products file, all that is left is to match the trade data with the filter by NAICS industry. Thus, letting M_{ij} denote total imports from a firm i in industry j , we categorize the firm's trade according to:

$$\left. \begin{aligned} M_{ij}^{\text{int}} &= \sum_{p \notin P_j} M_{ipj} \\ M_{ij}^{\text{fn}} &= \sum_{p \in P_j} M_{ipj} \end{aligned} \right\} \quad \text{where} \quad P_j = \{p \mid S_{pj} \geq W\}. \quad (\text{A1})$$

The bottom section of Table A3 shows summary statistics of the intermediate share of trade from this classification system, for several values of the product-threshold W . There are two important takeaways from these numbers. First, the share of intermediates in total imports for our baseline threshold value is roughly what is reported in the literature using IO Tables. Second, the share of total trade occupied by intermediate products is not particularly sensitive to the threshold level. While there is a small increase in the share when raising the threshold from 0 to our baseline of 0.1 (about 3 percentage points), the number is essentially unchanged when raising it further to 0.2.

A.3 Sample Creation

A.3.1 Constructing the Baseline Dataset

This section will discuss the steps taken to construct the sample used in Section 3.1.

Beginning with the raw files of the LFTTD export/import data, we drop any transactions with missing firm identifiers, and those corresponding to trade with U.S. territories. Next, we merge the LFTTD files with the HS-NAICS6 product concordance from Pierce and Schott (2012); if there is no NAICS6 code for a particular HS code, we set NAICS6 equal to XXXXXX. We then aggregate up to the level of Firm-Country-Month-NAICS6, and create extracts for three sets of

sources/destinations: Japan, Non-Japan, and North America (Canada and Mexico). Next, assigning each firm to an LBD-based industry, we run the NAICS-based trade codes through the intermediate/final goods filter discussed in Appendix A.2. The firms' monthly trade can then be split into intermediate and final goods components by source and destination groups. We repeat this step for years 2009, 2010, and 2011.

Using the LBD, we drop inactive, ghost/deleted establishments, and establishments that are not in-scope for the Economic Census. To create the sample of manufacturing firms in the U.S., we first create the firm-industry codes as described in Appendix A.2. We then drop non-manufacturing firms. Next, we merge the LBD for the years 2009-2011 with the DCA-Bridge (see Section A.1) containing multinational indicators. We then apply the rules specified above for clarifying disagreements with the DCA-based multinational indicators. We merge by firm-month to the trade data. Missing information in the trade data is replaced with zeros. Firms that do not exist in all three years are dropped from the sample.

Table A1: DCA Match Statistics: 2007-2011

	# of DCA Establishments	Matched to B.R.	Percent Matched
Total			
2007	112,346	81,656	0.73
2008	111,935	81,535	0.73
2009	111,953	81,112	0.72
2010	111,998	79,661	0.71
2011	113,334	79,516	0.70
U.S. Multinationals			
2007	22,500	16,396	0.73
2008	23,090	16,910	0.73
2009	22,076	16,085	0.73
2010	21,667	15,785	0.73
2011	21,721	15,557	0.72
Foreign Multinationals			
2007	10,331	7,555	0.73
2008	9,351	6,880	0.74
2009	11,142	8,193	0.74
2010	11,308	8,181	0.72
2011	11,619	8,357	0.72

Table A2: Uniworld Match Statistics: 2006-2011

	# of Uniworld Establishments	Matched to B.R.	Percent Matched
Foreign Multinationals			
2006	3,495	2,590	0.74
2008	3,683	2,818	0.76
2011	6,188	4,017	0.65
U.S. Multinationals¹			
2007	4,043	3,236	0.80
2009	4,293	3,422	0.80

¹U.S. multinationals include only the establishment identified as the U.S. headquarters.

Table A3: Appendix Table Comparing the Results from Threshold Values W

	Threshold Values		
	$W = 0$	$W = 0.1$	$W = 0.2$
<i>Number of Final Good Products per Industry</i>			
Median	19	1	1
Mean	25	1.52	1.14
Min	1	1	0
Max	154	6	3
<i>Implied Share of Intermediate Inputs</i>			
Imports	60.9	63.90	63.97
Exports	52.0	54.96	55.04

B Additional Results

B.1 GIS Mapping of Earthquake Intensity Measures to Affiliate Locations

As part of the Earthquake Hazards Program, the U.S. Geological Survey (USGS) produces data and map products of the ground motion and shaking intensity following major earthquakes. Their preferred measure to reflect the perceived shaking and damage distribution is the estimated “Modified Mercalli Intensity (MMI)” which is based on survey responses, measured peak acceleration and velocity amplitudes. The USGS extends the raw data from geologic measurement stations and predicts values on a much finer grid using seismological inference and interpolation methods. The result is a dense grid of MMI values covering the broad region affected by the seismic event. For more information on this methodology, see Wald et al. (2006).

To utilize this information, we take all Japanese addresses from the DCA/Uniwold directories that correspond to any U.S. operation via an ownership link. We geocode these addresses into latitude/longitude coordinates using the Google Geocoding API. We plot a heatmap of the earthquake intensity together with the affiliate locations in Figure B1.

B.2 Alternate Specifications for Treatment Effects Regressions

Our results from Section 3.2 are based on a sample including all Japanese multinationals in manufacturing, and therefore uses a levels specification to allow for zeros in the firm-month observations.

To explore how our findings depend on the specification in levels, we repeat the analysis on a subset of firms which have positive values of trade in every month. Specifically, we drop any firms with zeros in any month for intermediate imports or N.A. exports during the sample period, and then take logs and HP-filter each series to obtain percent deviations from trend for each firm. We then estimate specification (1) as described in Section 3.1. The results of this exercise are shown in Panel A of Figure B5. Due to the exclusion of zeros, the falls of both imports and output are smaller. Yet, they fall roughly one-for-one. We suppress standard errors for the sake of clarity in Panel A of Figure B5 but we note that the drops are significant at the 95% level for the months 2-4 following the shock.

If we re-run these regressions while also weighting according to the pre-shock size of firms, we obtain a picture that looks very similar to Figure 6, see Panel B of Figure B5. These results suggest that larger firms were more affected by the shock.

B.3 Effects on Unit Values (Prices) of Trade

The LFTTD contains information on quantities as well as values for each trade transaction, recorded at a highly disaggregated product definition (HS-10 digit). We can use this information to construct unit values (prices) for each firm-product-month observation, which allows for an analysis of price movements around the Tōhoku event.

Most of the data construction is identical to that in Section A.3, with a number of modifications. First, we drop all transactions with missing or imputed quantities in the LFTTD, and then aggregate

to the Firm-HS10-month frequency, separately for each type of trade transaction: 1) Related-Party imports from Japan; 2) Non Related-Party imports from Japan; 3) Related-Party exports to Canada/Mexico; and 4) Non Related-Party exports to Canada/Mexico. Next, we select only those firms identified as manufacturing in the LBD. We keep only those firms identified as a multinational in either 2009, 2010, or 2011.

B.4 Effects on U.S. Exports to Japan

Another potential dimension of the transmission of the Tōhoku shock to the United States is a change of U.S. exports back to Japan. To the extent that Japanese firms in the U.S. receive inputs from Japan for processing and re-shipment back to Japan, one might expect the U.S. exports to Japan fall following the Tōhoku event. On the other hand, U.S. affiliates may have increased shipments to Japan following the shock in order to offset the production and supply shortages within Japan. To evaluate the impact of the shock on U.S. exports to Japan, we re-run the specification in equation (1) but replace $V_{i,t}^M$, the value of intermediate imports of firm i in month t , with $V_{i,t}^X$, the value of Japanese exports. The results are shown in Figure B6. As is clear from the figure, there is little evidence to support either hypothesis. Differential U.S. exports to Japan remained roughly unchanged.

B.5 Domestic Inputs

The Standard Statistical Establishment List (SSEL) contains quarterly employment and payroll information for nearly all private, non-farm employers in the U.S. economy. This list is held separately as a single-unit (SSEL-SU) and multi-unit (SSEL-MU) file. The Report of Organization Survey (ROS) asks firms to list the establishments which report under a particular EIN, and this information is then recorded to the firm identifier on the Multi-Unit File. To build a quarterly employment series at the firm-level, we link the EIN variables on the SU file with the firm identifier linked with each EIN on the MU file. In principle, the four quarters of payroll listed on the SSEL is combined by Census to create an annual payroll figure for each establishment, which is the value recorded in the LBD. Similarly, the employment variable corresponding to the 1st quarter (week of March 12) from the SSEL is that used by the LBD.

Once we merge the SSEL-based data with quarterly employment and payroll to the LBD for a particular year, we conduct a series of checks to ensure that the annual payroll (and 1st quarter employment) roughly align. Any establishments with disagreements between the SSEL-based payroll and LBD-based payroll such that the ratio was greater than 2 or less than 0.6 were dropped.

After these modifications, the remainder of the data construction is similar to that in Section A.3. We merge multinational indicators from the DCA, drop non-manufacturing firms, restrict the sample period to 2009 to 2011, and keep only those firms that exist in each year. Using the same set of firms as a control group as specified in Section 3.1, we run the following regression:

$$\Delta \text{emp}_{i,t} = \alpha_i + \sum_{\tau=-3}^3 \gamma_{\tau} E_{\tau} + \sum_{\tau=-3}^3 \beta_{\tau} E_{\tau} \text{JPN}_i + u_{i,t} \quad (\text{B1})$$

where $\Delta \text{emp}_{i,t} = \ln(\text{emp}_{i,t}/\text{emp}_{i,t-4})$, where $\text{emp}_{i,t}$ indicates employment at firm i in quarter t . We also re-run the equation specified in equation (B1) using payroll $\Delta \text{pay}_{i,t}$ as the dependent variable. The results are shown in Table 3.

B.6 Accounting for Utilization Changes

To evaluate whether variable input utilization affects our estimates, we modify the production function to include a utilization term in the capital-labor bundle as follows:

$$x_{i,t} = \phi_i \left[\mu^{\frac{1}{\zeta}} (u_{i,t} K_{i,t}^\alpha L_{i,t}^{1-\alpha})^{\frac{\zeta-1}{\zeta}} + (1-\mu)^{\frac{1}{\zeta}} \left((\nu_i)^{\frac{1}{\omega}} (m_{-J,i,t})^{\frac{\omega-1}{\omega}} + (1-\nu_i)^{\frac{1}{\omega}} (m_{J,i,t})^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \right]^{\frac{\zeta-1}{\zeta}}$$

We then normalize utilization in period $\tau-1$ to unity and assume that utilization in τ is an isoelastic function of output with elasticity γ . That is

$$u_{i,\tau} = (x_{i,\tau})^\gamma.$$

If output $x_{i,\tau}$ falls relative to the previous period, then utilization will be adjusted downwards as well. Since we have no information on the magnitude of the elasticity γ , we estimate the model for several alternative values of γ . Table B1 presents the results for the ‘‘All Firms’’ sample with $\gamma = 0.3$ and $\gamma = 0.5$. There is little change in the estimates when allowing for variable utilization. We also conducted extensive Monte-Carlo simulations on artificial data and confirmed that the elasticity estimates vary little if the true elasticities ω and ζ are small.

B.7 Bootstrapping Standard Errors

We use bootstrapping to compute standard errors of our point estimates. Using random sampling with replacement within each group of firms, we create 5000 artificial samples and re-run the estimation procedure. For each of these samples, the non-Japanese materials share is imputed prior to estimation as described in Section 4.3. The standard deviation of the point estimates across these bootstrap samples is shown in Table 4. To gain a more complete picture of the dispersion, we create density estimates for each sample of firms. These densities are shown in Figure B8.

B.8 Correlation of Manufacturer Shipments and our Output Proxy

The best available information on actual shipments in the Census data is available annually from the Census of Manufacturers and Annual Survey of Manufacturers. We take the 2007-2011 panel of the ASM/CM and retain only those establishments that are in each year of the panel. We aggregate the shipments information to the firm-level, and then match this to the firms’ annual N.A. exports information, from the LFTTD. Then we drop those firms that have missing annual N.A. exports information, or those firms that report zero exports in the ASM/CM, but yet have positive N.A. exports. Using DHS growth rates, we calculate the correlation between the growth rates of shipments and the growth rate of N.A. exports for each firm, and then calculate the correlation.

B.9 Ward’s Automotive Data

Ward’s electronic databank offers a variety of data products for the global automotive industry at a monthly frequency. We obtain North American production (by auto manufacturer) for the period from January 2000 to December 2012. The series cover the universe of the assembly operations of finished cars and light trucks. The Japanese automakers are Honda, Isuzu, Mazda, Mitsubishi, Nissan, Toyota, and Subaru. We first construct car production for non-Japanese and Japanese automakers by summing the seasonally adjusted counts of cars and trucks produced. We use the X12-ARIMA model for seasonal adjustment. The two series are then logged and detrended using the HP filter with smoothing parameter 14400. We plot these series separately in Figure B3. The auto series in Figure 7 is the difference between the series for Japanese and non-Japanese automakers. We also estimated a dynamic treatment effects specification as in Section 3. While the sample is quite small, the results are very similar to the differential path in Figure 7.

B.10 The Product Composition of Imports

Section 3.1 interpreted the data through the lens of a representative Japanese firm, whereas Section 4 estimated the elasticities at the firm level. In both cases we aggregated across products in our measurement of imported intermediates. In this appendix, we discuss whether there were important product-level compositional changes within the Japanese imports of Japanese firms.

We construct a measure of the distance of a firm’s import bundle from a benchmark, where the benchmark bundle consists of all imports over the period from April to June of 2010. Let t^* be this benchmark date. Then, using the product-level information in the LFTTD data, we construct for each firm i , the share of total imports from Japan for a given product code p . Defining this share to be $s_{p,i,t}$, we then construct the average product-level distance from the benchmark as

$$D_{i,t} = \frac{1}{N_i^p} \sum_{p=1}^{N_i^p} |s_{p,i,t} - s_{p,i,t^*}|, \quad (\text{B2})$$

where N_i^p is the total number of products imported by firm i . We compute $D_{i,t}$ at a monthly frequency, with particular interest in the months following the Tōhoku event. One can calculate this measure at various levels of product aggregation (e.g. HS4, HS6, HS8, HS10), though we only report results using the HS6 level. This level of aggregation attempts to balance concerns along two dimensions. With less aggregation (e.g. HS10 level), there are concerns about the inherent lumpiness of product-level firm imports. This lumpiness makes $D_{i,t}$ noisy in the time series dimension. Greater aggregation, on the other hand, could mask important product differences within a particular product grouping.

While the behavior of measure (B2) generally depends on the product-level elasticity which is outside the scope of this paper, we showed in Section 3.2 that there were no systematic movements in import prices around the Tōhoku shock. As a result, at least in the months following the shock, changes in $D_{i,t}$ largely reflect changes in the quantity composition of imports. A sharp increase of $D_{i,t}$ would therefore imply that the input disruptions were specific to only a fraction of products.

The results of this exercise are shown in Figure B7, which plots the average $D_{i,t}$ across Japanese firms for each month (as well as the 3-month moving average) during the period 2009 to 2011. Mechanically, this measure should be relatively close to zero in the months defining the benchmark (April to June 2010). While there is a secular rise in this measure on either side of the benchmark period, there do not appear to be any abnormal jumps in the months directly following the Tōhoku event. The most likely explanation is that firms adjusted their product-level imports roughly proportionately after the shock. Alternatively, it is possible that the regular lumpiness of import shipments disguises any compositional changes induced by the shock.

B.11 Supplier Switching

The LFTTD data includes a variable that indicates the foreign “manufacturer ID” associated with a particular import transaction. We use this variable to assess the extent of supplier switching of Japanese affiliates during the time period surrounding the Tōhoku shock. We construct the number of Japanese and non-Japanese suppliers for each firm in 2008, 2010, and 2012 as well as the number of suppliers per HS code imported. We then calculate the number of “overlapping” suppliers, defined as the number of non-Japanese suppliers of a given HS code that overlap with the same HS code imported from Japan. This degree of overlap indicates the extent of diversification of country-specific risks in the firm’s global supply chain. Panel A of Table B2 looks at the change in Japanese suppliers, Japanese suppliers per product, and the degree of overlapping suppliers/products 2012 relative to 2010 and relative to non-Japanese multinational firms. Similarly, Panel B contrasts the change in the share of Japanese affiliates’ imports that are sourced from the same supplier in 2012-2010 to the same change between 2010-2008, again relative to non-Japanese multinational firms. The results show that the Japanese affiliates did not experience any abnormal or long-run supply chain effects following the 2011 Tōhoku shock.

Table B1: Firm-Level Estimation: Robustness to variable factor utilization

Estimates with Variable Utilization		
	$\gamma = 0.3$	$\gamma = 0.5$
ω	0.5141 [0.325 1.28]	0.5148 [0.330 1.28]
ζ	0.038 [0.035 0.038]	0.038 [0.035 0.038]
Sample:	All Firms (compare to Column 4 of Table 4)	

Notes: See Appendix Section B.6.

Table B2: Supplier Switching: Japanese Affiliates Operating in U.S. Relative to Other Multinationals

Panel A: (2010 vs 2012) Diff-in-Diff Coefficients

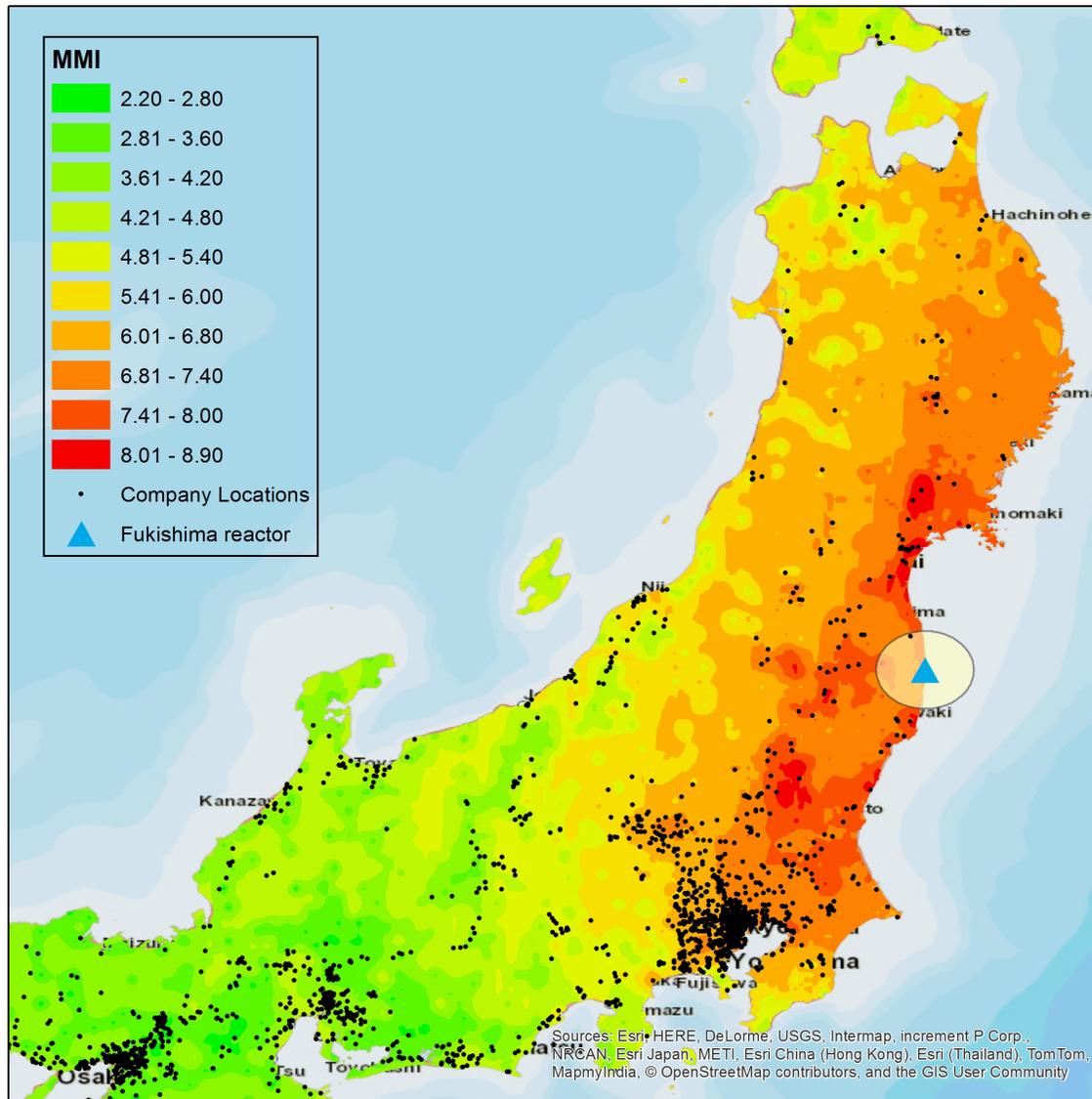
Dependent Variable	<i>JPN Affiliate</i>
Δ Number of JPN Suppliers	0.0226 (0.0806)
Δ Number of JPN Suppliers per Product	0.0310 (0.0361)
Δ JPN Supplier-Products with Overlapping Non-JPN Supplier-Product	-0.034 (0.094)
Δ Overlapping Non-JPN Supplier Products	-0.104 (0.109)

Panel B: Decomposing 2008-2010 vs 2010-2012 Supplier Switching

Dep. Variable:	<i>JPN Affiliate</i>
Δ Fraction of JPN Imports with Same Supplier-Product	0.0106 (0.032)

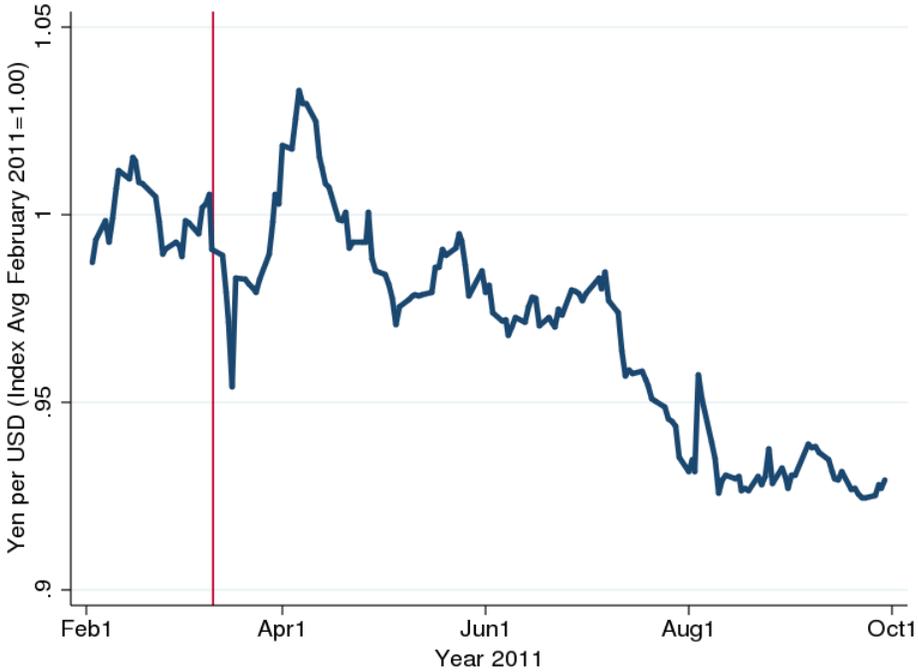
Notes: Source: LFTTD and DCA/UBP as explained in section B.11.

Figure B1: Geographic Distribution of Earthquake Intensity and Affiliate Locations



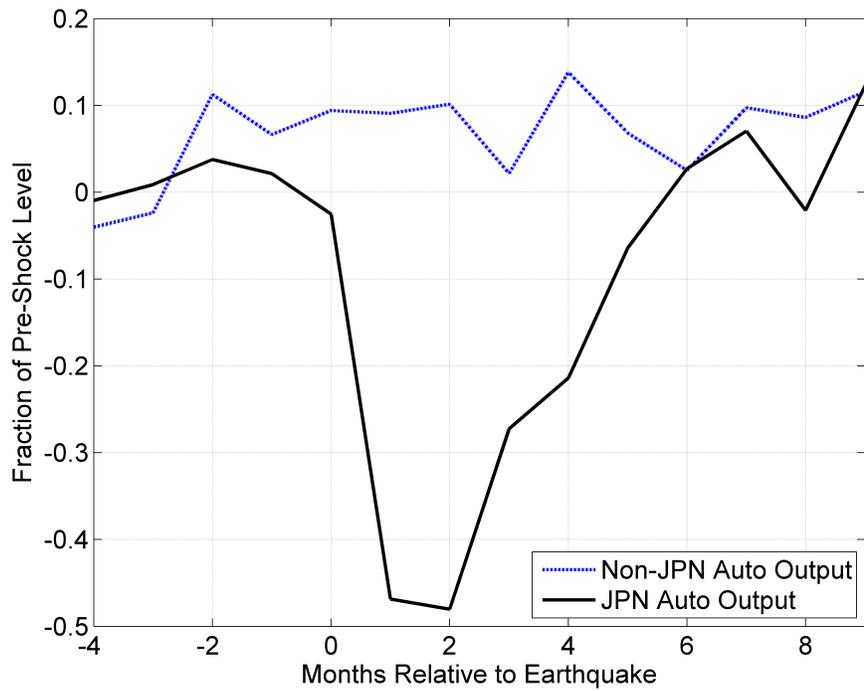
Notes: This figure plots the geographic distribution of the Tōhoku earthquake, based on recorded measurements taken directly after the event. The “Modified Mercalli Intensity” (MMI) scale is constructed based on survey responses, measured peak acceleration and velocity amplitudes from prior major seismic events. Each dot corresponds to a geocoded Japanese affiliate location corresponding to a firm with U.S. operations. For more details, see Appendix B.1. Sources: USGS, DCA, and UBP.

Figure B2: Index of Yen per U.S. Dollar Exchange Rate (February 2011 = 1)



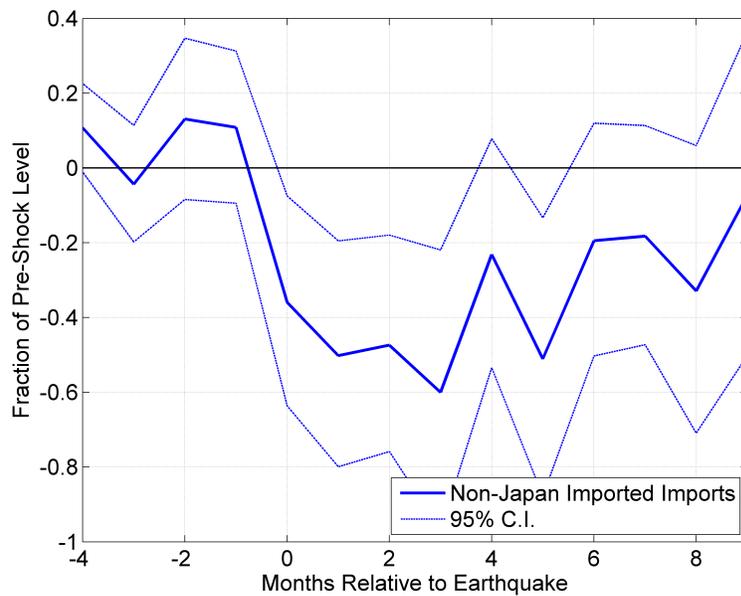
Notes: This figure reports the Yen per U.S. Dollar exchange rate, expressed as an index relative to the average for the month of February 2011. The red line indicates March 11, 2011. Source: IMF.

Figure B3: Automotive Production by Firm Type



Notes: The Japanese automakers are Honda, Isuzu, Mazda, Mitsubishi, Nissan, Toyota, and Subaru. The auto series are constructed by first summing the seasonally adjusted counts of cars and trucks produced, separately for all Japanese and non-Japanese manufacturers. These two series are then logged and detrended using the HP filter with smoothing parameter 14400. We then take the difference between the series for Japanese and non-Japanese automakers. Source: Ward's Automotive Database.

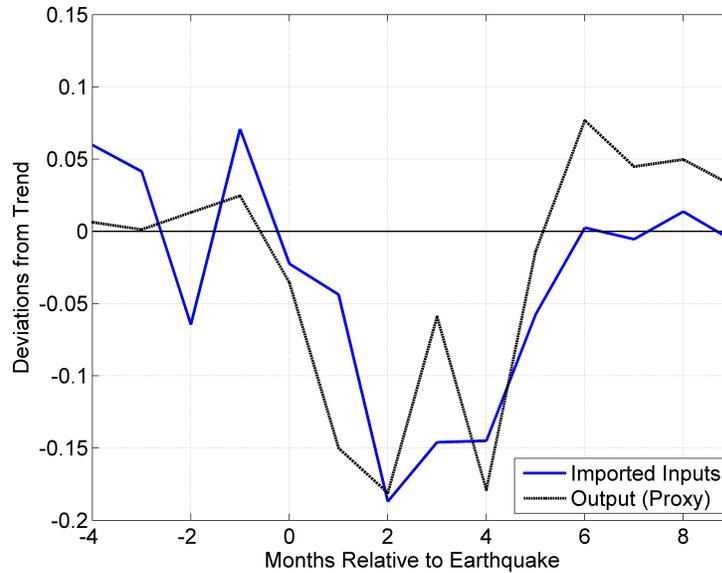
Figure B4: Relative Non-Japanese Imported Inputs of Japanese Firms: Fraction of Pre-Shock Level



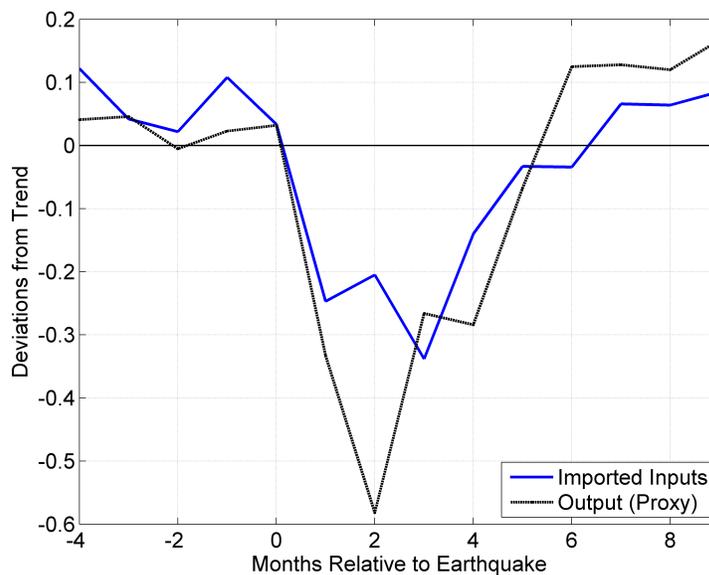
Notes: This figure reports the non-Japanese intermediate imports of the U.S. affiliates of Japanese firms relative to a control group of other multinational firms. The values are percent changes from the pre-shock level of each series, defined as the average of the months December 2010, January 2011, and February 2011. Sources: LFTTD, DCA, and UBP as explained in text.

Figure B5: Relative Inputs and Output (Proxy) of Japanese Firms (Reduced Sample)

A. No Size-Weighting

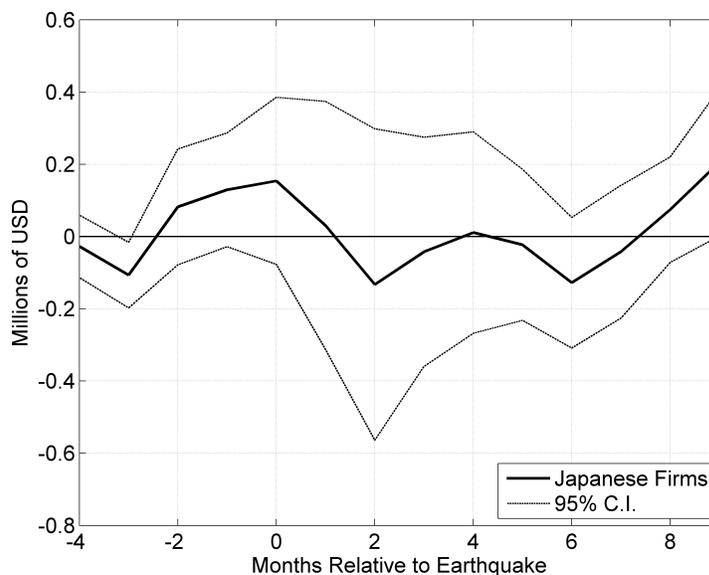


B. Size-Weighted



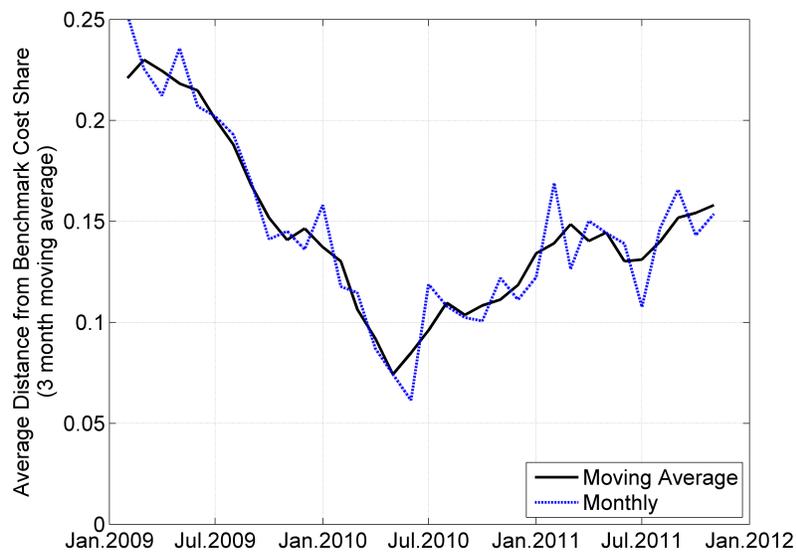
Notes: These figures report the percentage deviations from trend of Japanese affiliates relative to a control group of other multinational firms. The values are coefficient estimates taken from an interaction of a Japanese-firm dummy with a monthly dummy (see specification 1). The data are logged, and HP filtered using a monthly smoothing parameter 14400. Sources: LFTTD, DCA, and UBP as explained in text.

Figure B6: Dynamic Treatment Effects: Relative Japanese Exports of Japanese Firms



Notes: These figures report the Japanese exports of the U.S. affiliates of Japanese firms relative to a control group of other multinational firms. The values are coefficient estimates taken from an interaction of a Japanese-firm dummy with a monthly dummy (see specification 1). Standard errors are clustered at the firm level. Sources: LFTTD, DCA, and UBP as explained in text.

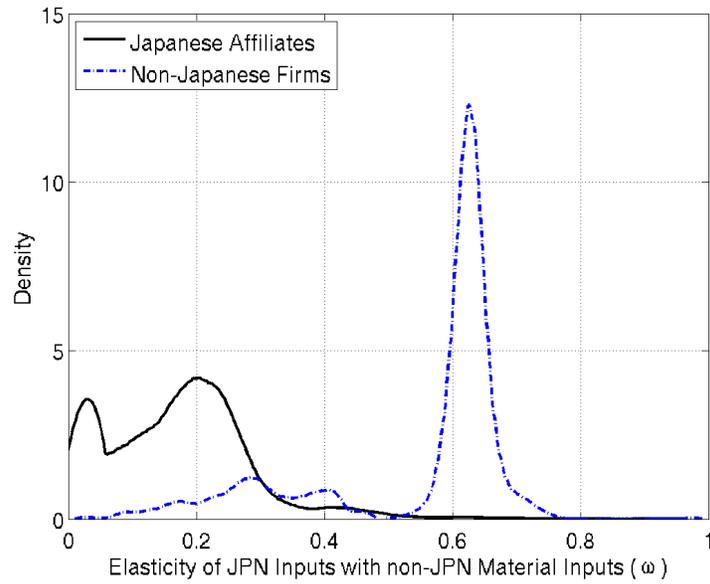
Figure B7: Product Composition of Japanese Imports: Distance from Benchmark



Notes: The figure illustrates changes in the product composition of Japanese imports as measured by the index given in equation (B2). The figure also shows a 3-month moving average of the same time series. See Appendix B.10 for details. Sources: LFTTD, DCA, and UBP as explained in text.

Figure B8: Density Estimates of Elasticities Across Bootstrap Samples

A. Japanese vs non-Japanese Multinationals: Materials Elasticity (ω)



B. Japanese vs non-Japanese Multinationals: Materials-Capital/Labor Elasticity (ζ)

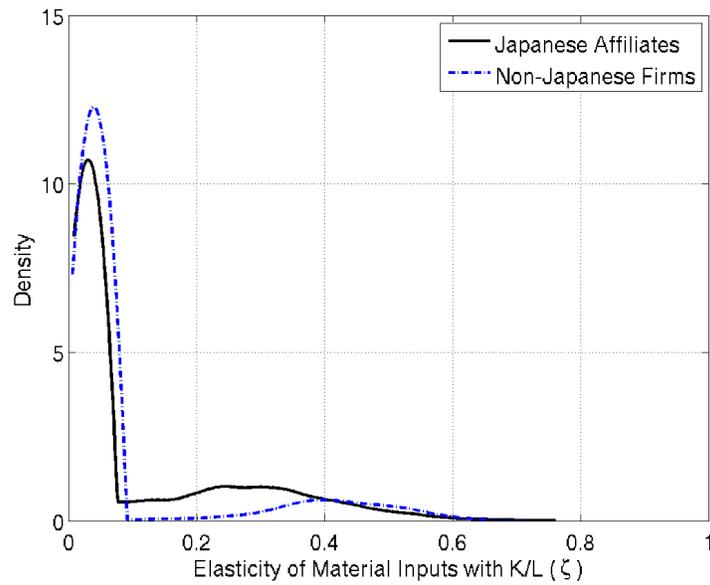
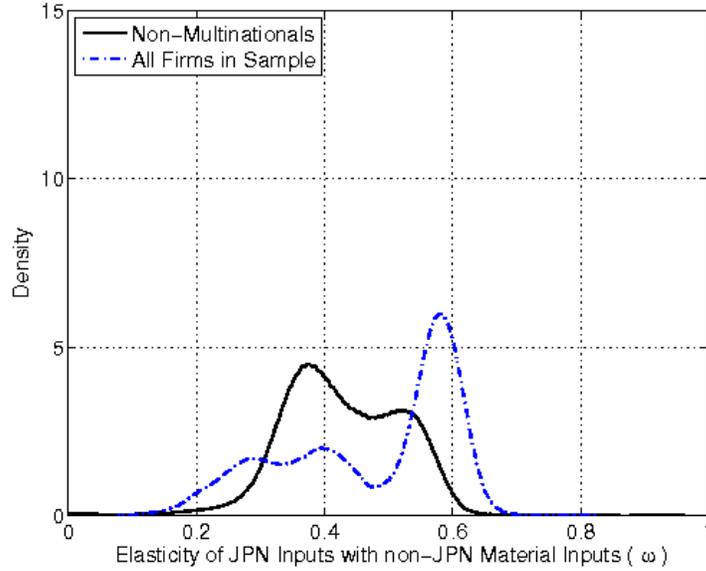
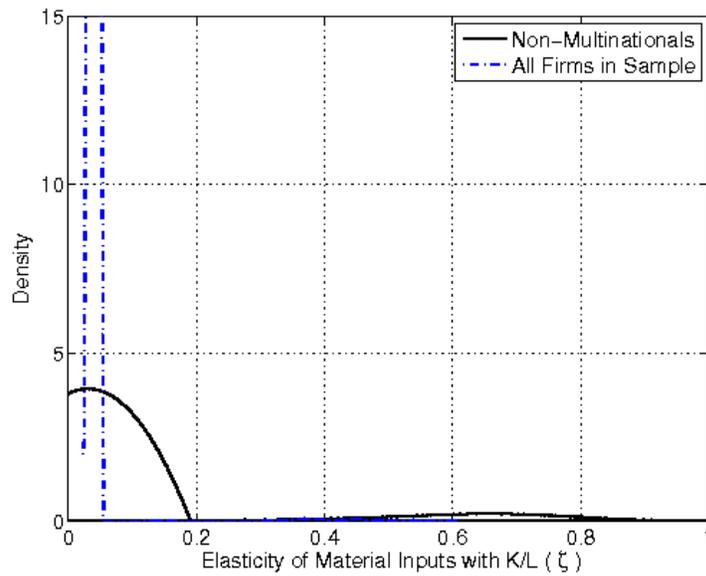


Figure B8: Density Estimates of Elasticities Across Bootstrap Samples

C. Non-multinationals and All Firms: Materials Elasticity (ω)



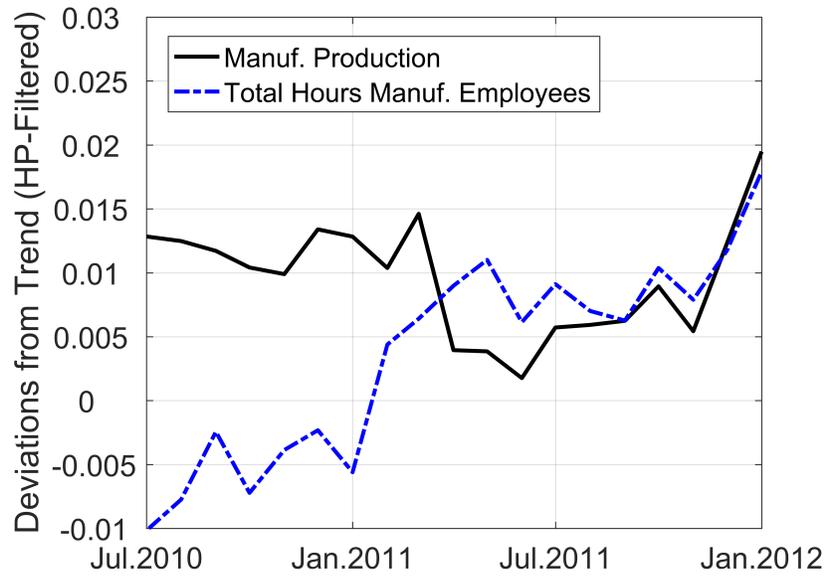
D. Non-multinationals and All Firms: Materials-Capital/Labor Elasticity (ζ)



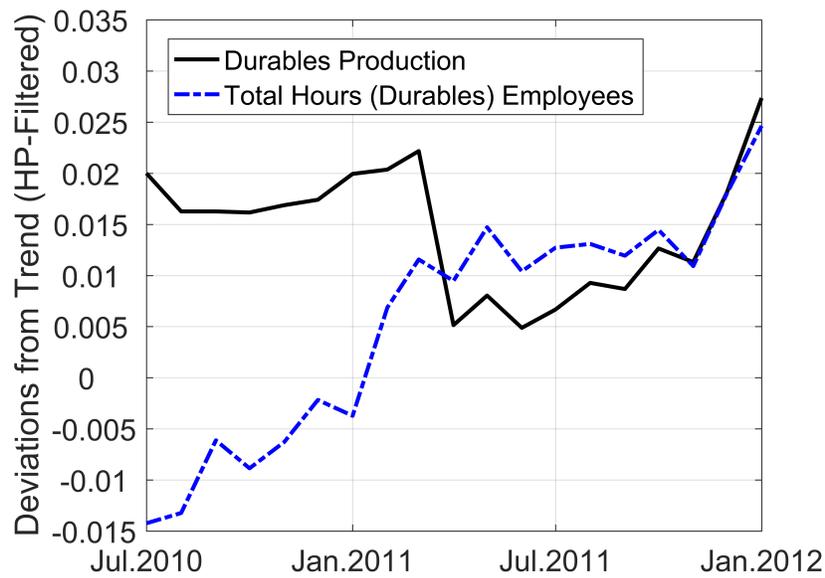
Sources: LFTTD, DCA, and UBP as explained in text.

Figure B9: Variable factor utilization

A. Industrial production and hours in the manufacturing sector



B. Industrial production and hours in durable goods manufacturing



Sources: Bureau of Labor Statistics and Federal Reserve Board