

INPUT LINKAGES AND THE TRANSMISSION OF SHOCKS: FIRM-LEVEL EVIDENCE FROM THE 2011 TŌHOKU EARTHQUAKE

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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 United States, output falls roughly one-for-one with declines in imports, consistent with a relationship between imported and domestic inputs that is close to Leontief.

I. Introduction

A WELL-ESTABLISHED fact in international economics is that countries with greater bilateral trade display greater business cycle synchronization (Frankel & Rose, 1998). Yet whether such comovement arises due to common shocks or endogenous spillovers, or both, remains the subject of much discussion (Imbs, 2004; Burstein, Kurz, & Tesar, 2008; di Giovanni & Levchenko, 2010; Johnson, 2014). Isolating specific mechanisms through which trade and foreign direct investment induce 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). Two advances in this paper permit a new evaluation of the nature and quantitative importance of these linkages. First, we use 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 data set that, for the first

time, links restricted U.S. Census Bureau microdata to firms' international ownership structure. This information permits a forensic focus on 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 0.

As disruptions to imports of final goods would be unlikely to affect the importer's production, we develop 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 22% 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 other 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 and 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 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., 2018), 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 intrafirm and arm's 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.

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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 and 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 and labor aggregates 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 United States, the elasticity estimates across all groups of firms are substantially lower than those typically used in the literature.

A number of important implications arise 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, & Pandalai-Nayar, 2014). This correlation increases by 11 percentage points when the elasticity of substitution of inputs is near 0 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. (2016) 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 nontrivial share of business cycle fluctuations (e.g., Carvalho & 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 United States where manufacturing production fell by about 1% (see also Atalay, 2017, and di Giovanni, Levchenko, & 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 Furthermore, one might worry that the composition of Japanese trade or firms engaged in such trade is not representative of United States 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 United States. Second, estimates for all firms in our sample also exhibit substantial complementarities, and as a whole, these firms account for over 70% 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 (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 III presents reduced-form evidence in support of a low elasticity of substitution for Japanese multinational affiliates. In section IV, we estimate firm-level elasticities in a structural model for several firm subgroups. Section V discusses the implications of these estimates, robustness, and external validity. The final section concludes.

II. Background and Data

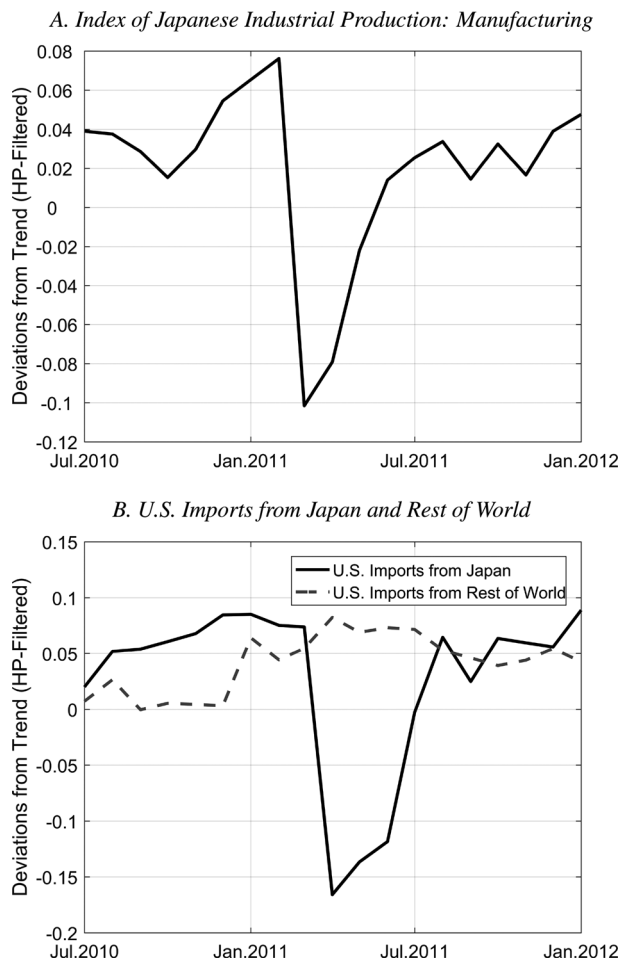
This section outlines the background of our event-study framework based on the 2011 Tōhoku earthquake and tsunami. We discuss the relevant details of this shock, document its effects in aggregate time series, and present the data underlying the subsequent empirical analysis.

A. 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 20,000 dead or missing and substantial destruction of physical capital. The magnitude of the earthquake was recorded at 9.0 on the

¹ Although our natural experiment is uninformative about long-run substitutability, Kremer (1993) and Jones (2011) show how complementarities play a key role in economic development.

FIGURE 1.—EFFECTS OF THE TŌHOKU SHOCK: JAPANESE PRODUCTION AND U.S. TRADE

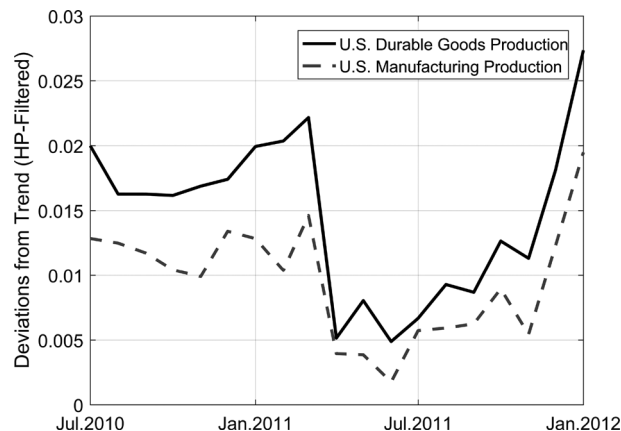


Sources: (A) Japanese Ministry of Economy, Trade, and Industry (METI). (B) U.S. Census Bureau, based on published totals.

moment magnitude scale (M_w), making it the fourth largest earthquake recorded in the modern era. 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 to 9 meters (23 to 29 feet), while the Port and Airport Research Institute (PARI) cite estimates of the maximum landfall height of between 7.9 and 13.3 meters (26 to 44 feet).

Figure 1A shows the impact of the Tōhoku event on the Japanese economy. Japanese manufacturing output fell by roughly 15% 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. 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,

FIGURE 2.—U.S. INDUSTRIAL PRODUCTION: MANUFACTURING AND DURABLE GOODS



Source: Federal Reserve Board.

delaying shipments to foreign and domestic locations. Yet, the largest Japanese ports (Yokohama, Tokyo, and Kobe), which account for the majority of Japanese trade, reopened 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 1B 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 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% drop in April, with a recovery by July 2011.

Particularly striking is the impact on the U.S. economy in the months following the shock. Figure 2 demonstrates a drop in U.S. manufacturing production. Although the magnitudes are much smaller—roughly a 1% drop in total manufacturing and almost 2% in durable goods—there is clearly a measurable macroeconomic effect.²

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. However, the short duration of the shock presents a challenge as it limits the available data sets with information at the required frequency.

B. Data

Several restricted-use Census Bureau data sets form the core of our analysis. The Longitudinal Business Database (LBD) collects the employment, payroll, and industry information of nearly all private nonfarm establishments

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

operating in the United States and is maintained and updated as described by Jarmin and Miranda (2002). Longitudinal linkages allow researchers 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 is 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, 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 allow us, for the first time, to identify the U.S. affiliates owned by a foreign parent company, as well as 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.³ Online 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 & 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 an industry to define a set of products intended for final sale for that industry.⁴ The remaining products are presumably used by establishments in that industry as either intermediate inputs or capital investment. Details on this classification procedure are available in online appendix A.2. In the aggregate, this classification yields values of the intermediate share of trade that are consistent with prior estimates: 64% of manufacturing imports are classified as intermediates in 2007.

The ideal data set 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, are 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 use a proxy based on the LFTTD: 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 Flaaen (2014) documented, exporting is a common feature of multinationals, of which exports to North America are by far the largest component. This fact alleviates concerns arising from conditioning on a positive trading relationship. We demonstrate in section VA that the quality of this proxy for output is high. In a separate data set containing high-frequency information on production for a smaller set of firms, we show that actual output tracks our proxy very closely.

III. 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 United States 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 macromodels, we estimate firm-level elasticities in the next section.

A. Framework

To study the transmission of the Tōhoku shock, we compare the behavior of directly affected firms in the United States to a control group of firms that were not directly affected. A natural measure for a firm's exposure to the shock is the cost share of Japanese imported inputs prior to the Tōhoku event. We construct this measure by taking Japanese imported inputs and dividing by all other inputs (including 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 2007, 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 3, show little overlap between these two distributions: there are few Japanese affiliates with low exposure

³ For information on the directories and linking procedure, see online appendix A.1.

⁴ We distinguish between intermediate and final goods from the perspective of an importing firm. For example, it is possible for a final good of one firm to be characterized as an intermediate for another firm in a different industry.

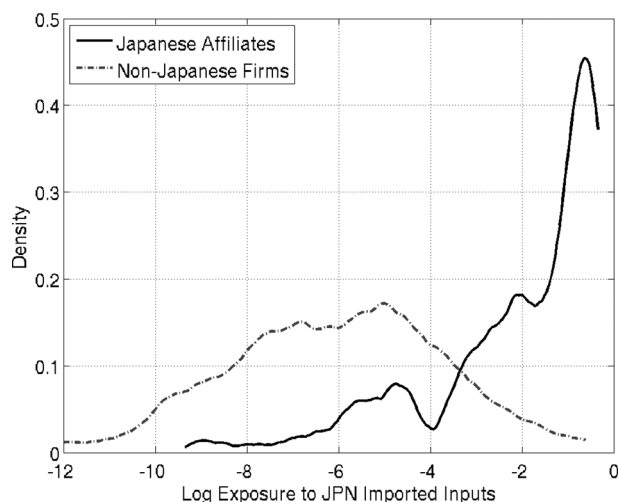
TABLE 1.—SUMMARY STATISTICS

	Japanese Firms	Nonmultinationals	Balancing Tests		% bias Reduction
	Japanese Firms	Other Multinationals	<i>t</i>	<i>p</i> -value	
A. Cost share of imported inputs					
From Japan	21.8	1.0			
From all countries	35.0	17.5			
B. Treatment effects sample details					
North American exports (USD)	3,504,894	3,413,058	0.38	0.706	79.1
Share intrafirm	72.0	52.2			
Intermediate					
Input imports (USD)	8,075,893	7,596,761	0.87	0.384	88
Of which: Share from Japan	70.0	3.5			
Of which: Share intrafirm	86.0	21.7			
Industry (arithmetic mean) ^a	—	—	—	0.965	97.8

Panel A data are for year 2007. The statistics for panel B are calculated for the three months prior to the Tōhoku earthquake: December 2010, January 2011, and February 2011. The control group of other multinational firms has been reweighted using the normalized propensity score; the final three columns report balancing tests of the equality of the means between the treated and control group for each variable.

^aDisclosure requirements prevent the listing of the test results for individual industries. The reported values are therefore arithmetic means. Sources: LFTTD, DCA, and UBP as explained in the text.

FIGURE 3.—DENSITY OF FIRM-LEVEL EXPOSURE TO JAPANESE IMPORTED INPUTS, BY FIRM TYPE



The exposure 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, Directory of Corporate Affiliations (DCA), and Uniworld Business Publications (UBP), as explained in the text.

to Japanese inputs and few non-Japanese firms with high exposure.⁵ 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.⁶ 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

⁵The exposure measure used in figure 3 is from 2010. Because 2010 is not a Census year, the exposure measure does not include the cost of domestic material usage.

⁶We also tried a threshold of Japanese input usage for the classification of treatment status. Due to the almost perfect separation shown in figure 3, this procedure yields very similar estimates.

number of competing methodologies for this type of estimation, we use normalized propensity score reweighting 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 U.S. and non-Japanese foreign—as our control group prior to reweighting. 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 after reweighting, the treatment and control groups are indeed comparable along these dimensions.⁷

In addition to the conditional independence assumption, consistent estimation of the mean effect requires that the control group is not itself affected 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%. 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. We also show in section VE that for a group of non-Japanese firms for which detailed data are 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 affects our estimation.

⁷Reweighting 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).

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} is 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 online 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 then divide this difference by the average preshock level of imports. Relative to an estimation in logs, the estimation in levels does not require 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 disruption. Dropping these observations would systematically remove those firms most affected by the shock and thereby bias the difference ΔV^M toward 0. Online appendix B.2 discusses alternative specifications that yield similar conclusions.

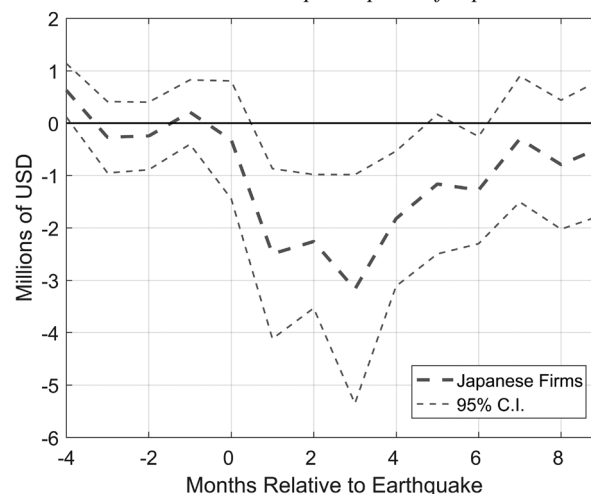
B. Results

The top panel of figure 4 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 per firm in $t = 3$ (June 2011) and the point estimates do not return back to the preshock trend until month $t = 7$ (October 2011).

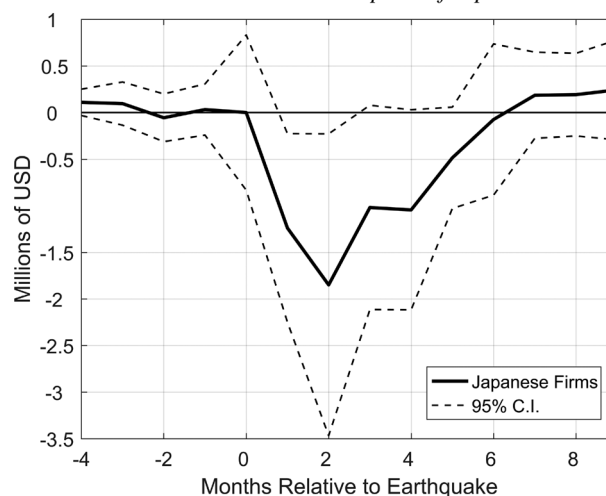
Figure 4B displays the impact on production of this shock on Japanese firms as proxied by their North American exports. This differential time path also exhibits a substantial drop following the Tōhoku event, hitting a trough of \$2 million below baseline in $t = 2$ (May 2011). Both panels

FIGURE 4.—DYNAMIC TREATMENT EFFECTS: JAPANESE FIRMS

A. Relative Intermediate Input Imports of Japanese Firms



B. Relative North American Exports of Japanese Firms



Sources: LFTTD, DCA, and UBP as explained in the text. See equation (1) in the text.

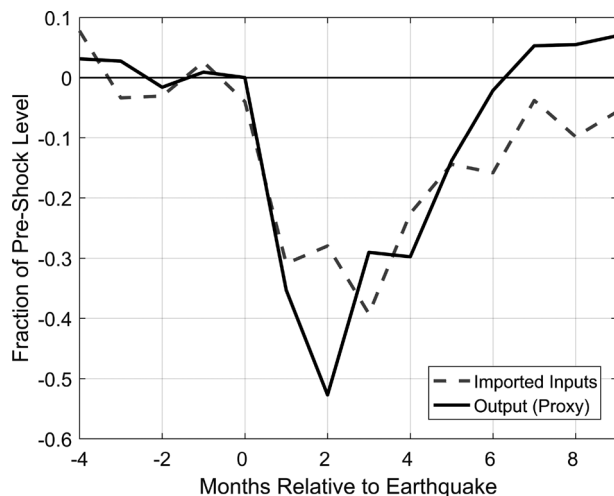
in figure 4 show 95% confidence bands, based on standard errors that are clustered at the firm level. These standard errors widen substantially on impact, reflecting the heterogeneous incidence of and recoveries from the shock across Japanese multinationals.

To compare the average percent drop in imports and production, we take the series of β_{τ} and divide by the average preshock level for these firms (see table 1). The results, plotted jointly in figure 5, show a remarkable correlation. There is essentially a one-for-one drop in output for a given drop in intermediate input imports.⁸

The analysis thus far 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

⁸ These firms show no differential effect on U.S. exports to Japan. See online appendix B.4.

FIGURE 5.—RELATIVE IMPORTED INPUTS AND OUTPUT (PROXY) OF JAPANESE FIRMS: FRACTION OF PRESHOCK LEVEL



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

by quantity; see online 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 and tsunami resulted in a brief yen depreciation relative to the U.S. dollar, implying a downward adjustment in dollar-denominated prices.⁹ To evaluate whether Japanese imports prices systematically changed during this time, we estimate

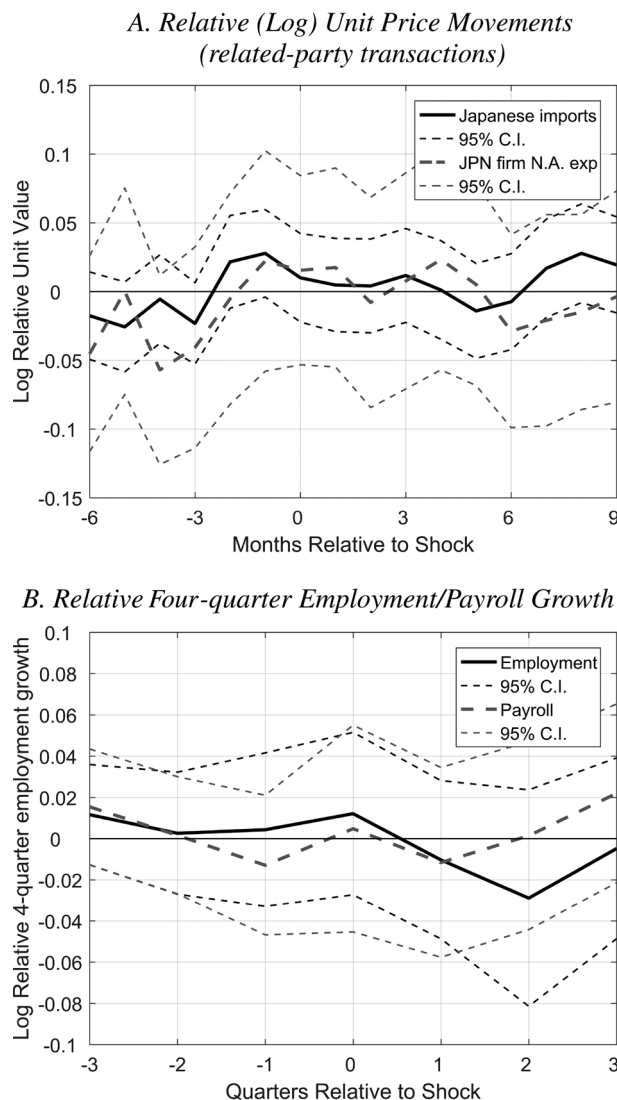
$$\log P_{i,k,t} = \alpha_{i,k} + \sum_{\tau=-19}^9 \gamma_{\tau} E_{\tau} + \sum_{\tau=-19}^9 \beta_{\tau} E_{\tau} JPN_{i,k} + u_{i,k,t}, \quad (2)$$

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), the indicator $JPN_{i,k}$ takes the value 1 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).

We estimate equation (2) separately for related-party and arm's-length transactions, as one might expect these prices to behave differently following a shock. We report the estimates of β_{τ} for related party transactions in figure 6A, as this category represents the substantial majority of both imports and exports of Japanese firms. As is clear in the figure, we do not observe consistently positive or negative responses for either imports or exports, and the estimates are small in absolute terms. This is also true for arm's-length transactions, which

⁹ The yen/dollar exchange rate changes during this time period were modest, roughly 2% to 3% relative to the March 10 value. See the online appendix for more details.

FIGURE 6.—RELATIVE TRADE PRICES AND EMPLOYMENT/PAYROLL GROWTH: U.S. AFFILIATES OF JAPANESE MULTINATIONALS



Panel A reports results for related-party transactions, which represent the large majority of total imports and exports of Japanese firms. The results for arm's-length transactions are available in online appendix table B1.

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

are reported in the online appendix. 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.¹⁰

C. Interpretation

We interpret these findings through the lens of a representative Japanese multinational firm with a standard constant

¹⁰ This finding is consistent with the publicly available time series of Japanese import prices from the International Price Program of the Bureau of Labor Statistics, which do not display any unusual movements around March 2011.

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 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 affected by the shock in Japan and there is no variable factor utilization. We return to both of these issues in sections IV and V.

We next translate the output elasticity of roughly 1 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 and labor with the fall in intermediate input imports. Then equation (4) implies that Λ must be near 1. This can be the case only if both $IM/\mu < F_D/(1 - \mu)$ and $\psi \rightarrow 0$. 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.¹¹ 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 reestimate specification (1) after replacing the left-hand side with measures of firms' employment and payroll. Figure 6B shows the results for a quarterly sample.¹² There is no evidence of a reduction of the workforce or payroll in the aftermath of the Tōhoku event. This

¹¹ This argument can easily be extended to a CES production function with more than two inputs. We discuss other ways of aggregating intermediate inputs in sections IVA and VF.

¹² Online appendix B.5 provides details on the creation of this quarterly sample.

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 scope for adjustments along this margin. The facts that capital is a stock while investment is a flow and that investment is also subject to adjustment costs imply that the capital stock is essentially constant in the short run (see House & 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 0. 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."¹³ Other news reports and press releases universally attributed the U.S. production impacts to shortages of parts coming from Japan.

IV. Structural Estimation

As the reduced-form evidence in section III 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 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.

¹³ See Associated Press (2011) for the full quote. 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.

A. Framework

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

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

where

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

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 ($\bar{m}_{i,t}^J$), including domestic materials.¹⁴ 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 v_i are weights, and ϕ_i parameterizes firm i 's productivity in the United States.¹⁵ Furthermore, 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 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., 2018) is to estimate how relative trade values respond to relative price changes. As we showed above, there was no significant response of measured prices in the aftermath of the Tōhoku disruption. This limits the available identifying variation and 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 that 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.

¹⁴ 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 discuss product-level elasticities in section VF.

¹⁵ In the estimation that follows, we assume that μ_i and v_i are constant within an industry.

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 v_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.

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 equations (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:

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

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

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

where

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

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 IIIC, 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 v_i , μ_i , and ϕ_i , which we back out from equations (9), (10), and (14), we estimate the elasticity parameters ζ and ω from how the firms' output covaries with its inputs. We assume that in period τ , firms operate the same production function given

by equations (5) and (6) and that no firm adjusts its capital stock such that $K_{i,\tau} = K_{i,\tau-1}$.¹⁶

B. Estimation

Recall that in section III, 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 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,

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

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

where the second equality uses production function (5).

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

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

Notice that κ_i and ϕ_i are not separately identified. We estimate the elasticities ζ and ω in equation (13) by non-linear 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 VA, 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

¹⁶ We have relaxed this assumption in robustness checks by assuming that equation (8) continues to hold in period τ . The results are similar.

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 affected 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 influence the estimates only for Japanese-owned firms. Since our results are similar across samples, it does not appear that ϕ_i was directly affected by the shock.

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

Two key advantages of this estimation procedure are that it does not require any assumptions on the form of adjustment costs faced by firms, and 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.

C. 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 those data from firm payroll and a semiannual rental rate of 7% for period $\tau - 1$. Recall that the capital stock is not adjusted over this time horizon so that $K_{i,\tau} = K_{i,\tau-1}$.¹⁷ We calibrate the capital share α to one-third, 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 IIIC.

Quarterly employment and payroll information comes from the Business Register.¹⁸ As discussed in earlier sections, the LFTTD contains firm-level data of Japanese imports and North American exports. For non-Japanese

¹⁷ The 7% rental rate is based on an annual real rate of 4% and an annual depreciation rate of 10%.

¹⁸ We adjust employment to reflect the average value over the six-month periods we study, which happens to align well with the timing of the earthquake. Specifically we set $L_{\tau-1} = 1/6 \text{Emp}_{2010Q3} + 1/2 \text{Emp}_{2010Q4} + 1/3 \text{Emp}_{2011Q1}$ and $L_\tau = 1/2 \text{Emp}_{2011Q2} + 1/2 \text{Emp}_{2011Q3}$, and analogously for payroll.

TABLE 2.—FIRM-LEVEL ESTIMATION: RESULTS AND SAMPLE DETAILS

A. Calibration				
Parameter	Value			
R_t	0.07			
α	1/3			
B. Estimation Results				
	Japanese Multinationals	Non-Japanese multinationals	Nonmultinationals	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				
Average weight on K/L aggregate ($\bar{\mu}$)	0.223	0.514	0.278	0.409
Average 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 international imports	0.60	0.23	0.03	0.86
Non-JPN international imports	0.02	0.66	0.01	0.69
North American exports	0.08	0.47	0.01	0.56

This table reports the results from the firm-level estimation detailed in section IV. Panel A outlines the parameters that are calibrated prior to estimation. The top two rows of panel B report the point estimates of the elasticities, and the corresponding 95% bootstrapped confidence intervals (see online appendix B.7 for more details).

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

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 use 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

$$\frac{P_i^M M_i - p_i^J m_i^J}{p_i^{-J} m_i^{-J}} \quad (14)$$

from the latest CM year.¹⁹ We use unit values at the HS10 level from the LFTTD to construct firm-level import and export price indexes.

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.²⁰ While this limits the number of firms in each sample, the shares of trade represented by these firms in each category remain very high (see table 2). We obtain standard errors using bootstrap methods, see online appendix B.7 for details.

D. Results

The results of the estimation are shown in table 2. The elasticity between material inputs for Japanese affiliates is 0.2, while the elasticity between the aggregate material input

¹⁹ We use industry-specific means for missing values and winsorize large outliers.

²⁰ Specifically, we drop any firm that has more than three months of 0s for any of these values, in period $\tau - 1$ or τ .

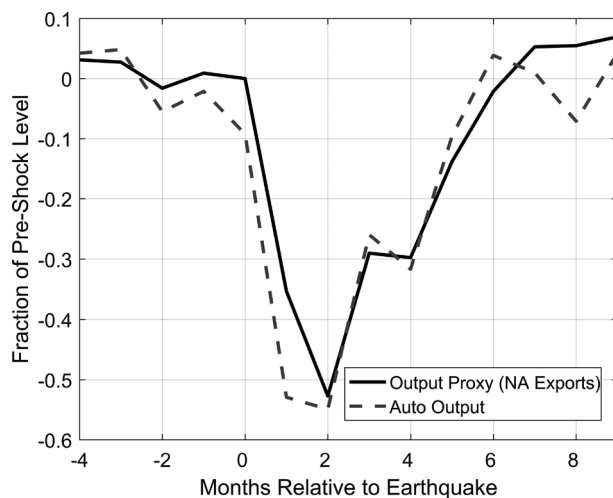
and capital and labor is 0.03. Together, these estimates are consistent with the evidence of little substitutability in section IIIB. The relative magnitudes of the point estimates are also intuitive: while Japanese imported inputs are strong complements with other material inputs, the estimates suggest that there is even less scope for substitution between material inputs and domestic capital and labor.

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 nonmultinational sample, the estimate is too imprecise to rule out values above unity. (For additional detail we plot the density of the elasticity estimates across bootstrap samples in online 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 samples indicates there were no direct spillovers to productivity ϕ_i due, for example, to headquarter effects.²¹

Although the number of firms included in this estimation is not large (550 firms 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 these data (see Bernard et al., 2007).

²¹ As is clear from the confidence intervals for these estimates, we cannot rule out that the elasticity estimates are the same across all four samples.

FIGURE 7.—ASSESSING THE OUTPUT PROXY USING MONTHLY AUTOMOTIVE PRODUCTION



LFTTD, DCA, UBP, and Ward's Automotive Database. See online appendix B.9 for details on the automotive data.

V. Robustness, Implications and External Validity

A. 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 output at the monthly frequency is available from Ward's electronic databank.²² Similar to our analysis in section III, we construct a series measuring how much auto production of Japanese automakers fell relative to 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, bottom out in May ($t = 2$) with troughs of 55% (auto series) and 53% (production proxy), and recover back to 0 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.

B. 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 upward, stacking the odds against finding a low elasticity. In fact, the extent to which we do not see any evidence of meaningful inventories of intermediate inputs is striking. In figures 4B 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. We find that Japanese multinationals hold a little over three weeks' worth of intermediate inputs as inventory. This is slightly less than nonmultinational firms (one month's worth of inputs), a fact that aligns well with the oft-cited just-in-time production philosophy pioneered by Japanese firms. Inventories of output are also low—roughly one to two weeks of shipments for both Japanese and nonmultinational firms.²³

The observations that input inventory holdings are low and 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 VG.

C. Strategic Behavior of Competitors

Our treatment effects specification in section III 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. In the online appendix, we evaluate this possibility using Ward's automotive data and consider the behavior of non-Japanese automakers in the months following the Tōhoku event. We find no quantitatively meaningful responses of non-Japanese automakers in the months following March 2011.

D. 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 assumption, we already showed that

²³ These numbers are broadly similar, though somewhat lower than other (usually older) estimates in the literature. See Ramey (1989) for one example.

²² See online appendix B.9 for further details.

TABLE 3.—FIRM-LEVEL ESTIMATION: ROBUSTNESS

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
B. Estimation Results: Motor Vehicle Sector				
	Japanese Multinationals		All Firms	
	Motor Vehicles	Nonmotor Vehicles	Motor Vehicles	Nonmotor 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
C. Other Robustness: All Firms Sample ^a				
	Varying Capital Share (α)		Three-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]

^a For the sample all firms, compare to column 4 of table 2.

Panel A recalculates the results from table 2 after weighting firms by their relative size (North American exports). Panel B divides the samples based on the motor vehicle industry. Panel C varies the calibration parameters and estimation window. Panels A and B use the same calibration parameters as table 2.

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

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 IIIC). 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 online 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 reestimated the model from section IV, 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 online appendix B.6 and online appendix table B2 for details.)

E. 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 reestimate the elasticities ζ and ω . The results, shown in panel A of table 3, are remarkably similar to our baseline estimates.²⁴

²⁴ The 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].

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 reestimate the parameters ζ and ω for the motor vehicle sector and its complement separately. The results are reported in panel B of table 3. 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 3 shows that our results are robust to alternate parameter values for the capital share parameter α (columns 1 and 2), the estimation window (column 3), and focusing exclusively on differentiated goods according to the Rauch (1999) classification (column 4).

F. The Product Composition of Imports

In the empirical analyses of sections III and IV, 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.

In online appendix B.10, we take one additional step and analyze the data at the product level. We find 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.

G. 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 that we design and calibrate to match key aspects of the data (Boehm et al., 2014). Relative to earlier work, our model differs in three dimensions. First and most important, 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 and 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 and tsunami. We find that relative to an alternative model without vertical linkages, GDP comovement increases by 11 percentage points. As in earlier contributions, the main mechanism is that strong complementarities synchronize intermediate input demand across countries (Backus et al., 1994; Heathcote & Perri, 2002; Burstein, Kurz, & Tesar, 2008).²⁵

Our evidence for input complementarities has implications for the transmission of shocks through production networks more generally. In fact, when we reestimate our dynamic treatment effects specification from section IIIA, 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 online 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 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., 2016).

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 0. 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 the closest in spirit to those we estimate in this paper, are generally less than 0.2 and always less than 1, similar to our estimates.²⁶

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 United States, where manufacturing production fell by 1 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 & 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. Kurz and Senses (2016), however, show that firm-level employment volatility is increasing in the share of imported intermediate inputs, as well as the number of import locations.

H. 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 Flaaen (2014) showed, over 45% 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%, the share from the source country for all foreign affiliates is still a substantial 12%. Finally, the cost share of all imported inputs in total inputs is 35% for Japanese affiliates and 32% for all foreign affiliates.

Second, it is likely that disruptions to trade linkages comprising primarily 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% of U.S. imports from Japan are in differentiated goods. On the other hand, 84% of U.S. imports from other countries are also differentiated goods,

²⁵ For additional work on the role of intermediate input trade and multinational firms in business cycle comovement, see Johnson (2014), Arkolakis and Ramanarayanan (2009), Zlate (2016), and de Soyres (2016).

²⁶ See also Bigio and La'O (2016), and Baqaee (forthcoming).

which is lower but nevertheless a sizable fraction.²⁷ When 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 that are somewhat informative about the long run. First, online 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 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. (2018) 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. Changing the time horizon to five years increases these estimates, but the differences are small.²⁸

VI. Conclusion

In this paper, we showed that input linkages with strong complementarities are a key mechanism through which shocks are transmitted across borders. We used the Tōhoku earthquake 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 inputs is near 0 in the short run. Structural estimation at the firm level confirmed this result.

²⁷ This definition follows the “naive” categorization used in Bernard, Jensen, and Schott (2006): two-digit HS-industries 01 to 21 and 25 to 29 are classified as commodities.

²⁸ We thank Philip Luck for helpful discussions and sharing their code. The elasticities estimated here do not correspond to ω or ζ , but rather are similar to the elasticities in that paper.

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 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 determinants of inventory holdings are an important topic for further research.

While it is well understood that domestic and foreign varieties are imperfectly substitutable, the degree of complementarity and its implications in the short run have received less attention. This paper 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 to understand the time frame over which adjustments to supply chains occur and whether such 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, & Szeidl, 2015). Allowing for such adjustments will permit a more complete assessment of the contribution of input complementarities to aggregate fluctuations and the transmission of shocks through production networks.

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