The Aggregate Effects of Global and Local Supply Chain Disruptions: 2020–2022*

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Abstract

We study the aggregate effects of supply chain disruptions in the post-Pandemic period in a two-country heterogeneous-firm general equilibrium model with a rich set of supply chain frictions: shipping delays, fixed order costs, storage costs, uncertain delivery, and uncertain demand. These frictions lead firms to hold inventories that depend on the source of supply and these inventories influence price setting and are an input into production. We model aggregate shocks that capture the dynamics of the global economy in the crisis and recovery. We show that increases in shipping times are contractionary, raise prices and increase stockouts, particularly for goods intensive in delayed inputs. These effects are larger when inventories are already at low levels, as in the U.S. and the world since early in the Pandemic. We fit the model to the key features of the aggregate economy from 2020-2022 and estimate the aggregate effects of international and domestic supply disruptions. Our model predicts that the boost in output from the unwinding of restocking delays will be smaller than the contraction in output from the waning effects of stimulus in 2021.

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1 Introduction

Since the onset of COVID, the reopening of the global economy has been hampered by large and unprecedented supply-chain disruptions that have substantially increased both the costs and time involved in moving goods within and across borders. For example, from the start of the Pandemic through February of 2022, the costs of shipping goods from Asia to the United States by air has nearly doubled while the costs of long-distance trucking in the United States have risen almost 25 percent. Accompanying these cost increases has been a large increase in delivery delays. The ISM delivery times index shows that the average lead time for materials and inputs has risen by about 35 days in the United States. The IHS Markit survey of global purchasing managers shows a similar increase in delays for the Euro area (Figure 1) and a general increase in delays worldwide. While the focus has been largely on delays at ports, which are processing record trade volumes, these delays are also present in purely domestic transactions. The higher costs and longer lead times come at a time in which inventories relative to sales in certain sectors in the United States are at historically low levels, making it hard for firms to adjust and leading to a worldwide increase in retail stockouts, particularly for imported goods (Cavallo and Kryvtsov, 2021).

In this paper, we quantify the aggregate effects of supply-chain delays experienced in the United States and the rest of the world (ROW) in the post-COVID period.[1] A key challenge to our analysis is that the unique features of the current environment—increased delivery times and depleted inventories—are absent in the standard macroeconomic and trade models used in policy or business cycle analysis. For our purposes, we apply the heterogeneous firm model developed by Alessandria et al. (2022)—used to study supply disruptions in an earlier, less globally integrated, era—to these current events. In this model, firms use imported and domestically produced goods that take time to arrive after being ordered subject to a fixed cost. This delay is costly and uncertain. Firms also face idiosyncratic demand shocks, so they optimally hold costly inventories to guard against stocking out and missing sales.

In this model, we consider an increase in international delivery times from 55 days to 90 days, mirroring the recent U.S. experience. The shock is transitory, but persistent. As firms

[1] By "post COVID" we mean "following the onset of COVID"—March, 2020.

run down inventories, they optimally raise prices and consumer prices rise by more than seven percent from their steady-state value. The increase in shipping time is contractionary, lowering output in the traded goods sector by as much as 12 percent on impact. The large impact of this shock arises because it is not spread equally across all firms and constrains the sales of the firms for whom restocking is most valuable - those with relatively low inventories or relatively high demand.

The effects of the shipping delays are magnified if the shock arrives when inventories are low or consumer demand is high. Inventories in the United States were historically low in early 2021, reflecting the manufacturing shutdowns and closure of borders that were meant to mitigate the impact of COVID along with the modest changes in consumer expenditures on goods. The easing of COVID restrictions, changing pattern of spending, and significant government stimulus raised consumer expenditures as shipping delays increased. With low inventories and high consumer demand, prices increase more and inventories are driven to lower levels, suggesting that continued stimulus in the face of supply constraints will likely push prices higher.

In section 6, we use the model to recover a set of domestic and foreign shocks that can match the salient features of the global economy in the COVID collapse and recovery period in terms of the usual macroeconomic time series - production, sales, inventories, trade and the trade balance—plus our delivery time oriented series. By shutting down the delivery delay shocks we can estimate the aggregate impact of these supply frictions. Generally, we find that the delays were a substantial drag on economic activity in the United States and the ROW, particularly in 2021. As the delays continue to be high into 2022, they represent a continued drag on economic activity through 2022 and into 2023 and a key source of elevated prices.

We undertake an analysis of the increase in global and local supply chain frictions on the global economy in a two-country version of the heterogeneous firm model of Alessandria et al. (2022). The model here extends the two-country sS inventory model of Alessandria et al. (2010b) to include an input-output structure and sectoral heterogeneity in the use and consumption of domestic intermediates. That model has been shown to capture the cyclical behavior of trade, inventories, prices, and aggregate economic activity in the Great Recession and, more generally, over the business cycle. A key feature of the approach is that it explicitly models the differential costs in time, resources, and risk for domestic and international transactions. These risks are reflected in the different inventory management approaches used for imported and domestic transactions. For example, goods involved in international trade are held in inventory about twice as long as goods in domestic transactions (Alessandria et al., 2010; Nadais, 2017; Khan and Khederlarian, 2020), and inventory accumulation and depletion in international transactions are particularly sensitive to business cycles and policy shocks (Khan and Khederlarian, 2021; Alessandria et al., 2019). These kinds of differences between international and domestic transactions allow us to discipline the parameters of our model with firm-level data on inventories and ordering behavior.

Our paper builds on a recent, largely micro-oriented literature that studies the effects of supply disruptions on firms, to consider the aggregate implications. Barrot and Sauvagnat (2016) show that natural disasters that constrain production of upstream suppliers can have large and persistent effects on downstream firms' values and production. They find these effects are partly mitigated for firms with a relatively large stock of inventories. Several papers use the Tōhoku earthquake and tsunami to identify and quantify firm-level disruptions. Boehm et al. (2019) show that firms that use inputs from Japan reduce output one-for-one with imports. Carvalho et al. (2020) study the firm-level impact of the Tōhoku shock and quantify its aggregate effects in a closed economy general equilibrium model with production linkages. Our own earlier paper studies the aggregate effects of these types of shocks on the U.S. economy since 1950. Several recent papers have studied the effect of COVID in the presence of global production networks (Cakmakli et al., 2021; Bonadio et al., 2021) but do not consider the types of supply constraints related to time. Recently, Cavallo and Kryvtsov (2021) has shown that COVID has substantially and persistently increased the retail stock out rate in the U.S. and global economy. Motivated by our research, and consistent with our model, they also show that goods with a larger import content are taking longer to restock and that prices have risen by more for these goods. Our paper is also related to general equilibrium models of inventory management and business cycles (Khan and Thomas, 2007; Iacoviello et al., 2011; Ortiz, 2021).

Our paper is also related to work that estimates the effects of timeliness on trade flows.

Djankov et al. (2010) introduce a measure of "time to trade" into a gravity analysis and find that an extra shipping day lowers trade by more than one percent—more so for time-sensitive products. Hummels and Schaur (2013) use variation in shipping times to different ports and transport modes in the United States and estimate a tariff-equivalent time cost of 0.6–2.1 percent per day in transit. Clark et al. (2014) use variation in arrival rates to the same port to estimate that 10-percent more delivery uncertainty (about 0.5 a day) lowers trade by 1–2 percent. Related, Feyrer (2019) use the change in geography from the introduction of faster air transport to estimate relatively large effects of trade on income.

The paper is organized as follows. In Section 2, we summarize the evidence on input lead times and inventory levels. We also summarize the dynamics of the aggregate economy. Section 3 lays out the model. In Section 4, we use data, such as inventory holding and order frequency, to parameterize our model. In Section 5, we study the output and price effects of a persistent increase in shipping times in our baseline model and some variants. We also consider the effects of these shocks in conjunction with stimulus and out of steady state when inventories are low. In Section 6 we consider a combination of home and foreign shocks to shipping times, productivity, and stimulus that best account for the salient features of the U.S. and global economy in the COVID collapse and recovery. Section 7 concludes.

2 Data

We summarize some salient features of the U.S. and global economy in a three-year window around COVID. These features are related to increases in input lead times and substantially depleted inventories. For many of these series the changes are unprecedented in recent memory. Of course, the shock and policy actions were unprecedented too.

Lead times. It is taking much longer than usual to get inputs for production or sales. These delays vary across industries and by direction of trade. They reflect delays in the time between order and shipment and the time from shipment to delivery. We have already noted that global measures of lead times, measured by the IHS Markit diffusion indices, increased substantially with COVID and have only gotten worse. Figure 2 plots various measures from the Institute for Supply Management (ISM) lead times index which is a survey of U.S. purchasing manager on the time from order to delivery for various important inputs. An advantage of this series compared to a diffusion index is that it yields a time series of the level of delays that we can use to discipline our model parameters. There are four panels of delivery times. The first three show average lead times, in days, for production materials, capital expenditures, and maintenance, repair, and operating (MRO) supplies.[2] The last panel is a diffusion index that summarizes the direction of delivery times, with numbers above (below) 50 reflecting an increase (decrease) in delivery times. All four panels display levels in 2021 that have not been experienced in last 25 years. Production material delivery times were stable in the 2000s at about 45–50 days, drifted up to about 60 days following the Great Recession, and have risen to almost 100 days since the start of 2021. It is uncertain how persistent these recent changes in lead times may be. For instance, following the Great Recession the rise in lead times was quite persistent.[3]

An alternative measure of the time to restock is the ratio of unfilled orders to shipments (measured in days), which have also risen substantially. Figure 3 plots the unfilled orders of capital equipment excluding defense and aircraft from the Census against the ISM series on lead times on capital expenditures. Both series show a large and persistent increase in the days to delivery, although the unfilled order series shows an earlier, but smaller, increase than the ISM series. International transactions have been more affected than domestic transactions by supplier delays. In Figure 4, we plot a measure of delivery challenges, by type of transaction, from a survey of U.S. firms conducted by the Census Bureau that began at the early onset of COVID. Firms are surveyed about delivery delays on supplies by source (domestic and foreign) as well as their own delays. Firms reporting delays by foreign suppliers have more than doubled from the beginning to end of 2021 while domestic and own delays have risen by about 50 percent. These delays are concentrated in the tradable sectors (measured by inputs): construction, manufacturing, retail, and wholesale sectors. Figure 5 shows that these delays are especially large in international shipping, as the time to ship measured by ocean shipment transit time from China to the United States has risen by almost 40 days (from 41 to 80 days), from the end of 2019 to the end of 2021.

[2]Firms are asked to describe lead times by windows and then these times are converted to an average.

[3]Carreras-Valle (2021) attributes this secular rise in delivery times to a shift to more distant trade partners, particularly China, while Alessandria et al. (2022) attribute variation in lead times over a longer period to changes in local and global sourcing along with new modes of transport.

Inventories. The current level and distribution of inventories across sectors is quite unusual. Figure 6 plots a time series of U.S. inventory-sales ratios for three major sectors: manufacturing, retail trade, and an aggregate that includes those two sectors plus the wholesale trade sector. Two things are apparent. First, inventory-sales ratios have fallen in all sectors since the start of the crisis, but the decline has been largest in the retail sector, as retailers have moved from about 1.5 months of inventory to about 1.1 months (a record low). Second, the traditional structure of inventory holdings across sectors has been upended, with retail—normally the most inventory-intensive industry—becoming the least inventory-intensive.[4]

The low levels of retail inventories have greatly reduced the availability of goods, especially for imported goods. Using online data from retailers, Cavallo and Kryvtsov (2021) show that the onset of COVID lead to a substantial and persistent rise in retail stockouts globally. These stockouts were more common in the United States and remain at elevated levels through May 2022, even as aggregate measures of inventory-sales ratios are recovering. Importantly, they also show that these stockouts are more common and last longer for imported goods, consistent with our findings that delivery challenges have risen by more for international transactions.

The persistently high stockouts point to a challenge in interpreting the inventory data during this period. Inventories can be held at various stages of the supply chain and by various owners. For instance, longer shipping times between ports or dwell times for containers at the ports may lead those goods to be included in retail, wholesale or manufacturing inventories but will not be available for production or consumption. Moreover, inventories that are ultimately used in one country may be on the books of its trading partner.

Production, sales, and trade. Finally, we summarize the response of the aggregate economy to the pandemic and the supply disruptions that followed. Figure 7 plots some key variables of interest. These variables, along with our measures of delays and inventories, are the key moments we seek to interpret through the lens of the model. The first three panels are relative to their levels in the fourth quarter of 2019. From the first panel, we see that

[4]The inventory-sales ratio for motor vehicles has reached a record low. There are important challenges to rebuilding the stock of autos as lead times for parts have risen sharply due to several factors.

industrial production in manufacturing fell sharply in the United States and the rest of the world by about 20 percent. The recovery was relatively fast however, especially in the rest of the world, which, by the fall of 2020, was producing more than it had pre-crisis. Most of the movements in industrial production in the United States reflect the dynamics of employment and not productivity, particularly the decline and rebound.

Turning to the second panel, sales of goods (manufacturing plus wholesale and retail trade) in the United States also fell sharply but by considerably less than production. Sales rebounded faster than production and have remained about five percent above pre-crisis levels. Real consumption of goods fell even less and rebounded even more strongly. These expenditures accelerated at the end of 2020, and remain 15–20 percent above the level prior to the crisis. To fill the gap between production and sales, firms ran down inventories and the United States ran larger trade deficits.

In the third panel, we see that international trade (exports plus imports) fell about as sharply as production but rebounded faster and lagged overall sales and real consumption of goods. The trade balance, measured as the export-import ratio, is plotted in the fourth panel. The United States was exporting less than it imported before the pandemic and the drop in exports in 2020 was larger than the drop in imports. The drop in overall trade suggests that the shocks have had a relatively large effect on trade and the drop in the export-import ratio speaks to the relative size of shocks in the United States and the rest of the world.

Caveats. The data are not generally informative on the source of the delays. These delays may reflect capacity constraints owing to restrictions on input availability or high demand. These delays may be related to transportation infrastructure, public health restrictions, or production constraints. Knowing the source of delay is primarily important for determining the optimal policy response, but not the aggregate effects of these delays. Thus, we do not take a stand on the source of the delays in restocking inputs.

3 Model

In this section, we describe a two-country dynamic general equilibrium model with heterogeneous firms facing domestic and international transaction frictions that lead them to hold inventories. It extends the closed-economy model developed by Alessandria et al. (2022).

There are two sectors: 1) a *manufacturing sector* that combines labor and intermediate goods to produce and 2) a wholesale/retail sector (for brevity, the *retail sector*) that purchases goods from manufacturers, differentiates them, and sells the differentiated goods to consumers and the manufacturing sector. The retail-sector firms order domestic and imported inputs to sell at home subject to source-specific delay shocks and face idiosyncratic demand shocks. These two sources of uncertainty, demand and supply, affect the timing of a firm's orders and the prices they set. In general, firms want to avoid stocking out of their products to maximize profits. Unsold goods can be saved in inventory to be sold in future periods, but they incur a holding cost that depends on the interest rate and a product's depreciation rate.

3.1 Shipping delays

Retail firms place orders after observing their idiosyncratic demand shocks but before setting prices. Goods ordered at the beginning of the period arrive within the same period with probability $1 - \mu_i$, where $i \in \{D, I\}$ denotes an order from a domestic supplier or an international supplier. With probability μ_i the goods are delayed and arrive in the next period. We assume that μ_{it} follows a stochastic process defined by

$$\mu_{it} = \rho_\mu \, \mu_{i,t-1} + (1 - \rho_\mu)\bar{\mu}_i + \varepsilon_{\mu_i t}, \tag{1}$$

where ρ_μ is the persistence of the shock and $\bar{\mu}_i$ is the steady-state probability that goods from source i are delayed and arrive in the next period. Thus, a positive $\varepsilon_{\mu i}$ increases the average shipping delay faced by firms.

3.2 Households

There are two symmetric countries, Home and Foreign, populated by a unit mass of identical agents that are modeled as representative households. Foreign-country variables are denoted with an asterisk. Households in Home and Foreign supply labor, consume, and trade state-contingent bonds. The aggregate state is η_t, a history is $\eta^t = (\eta_0, \eta_1, ..., \eta_t)$ and the probability of a history is $\pi(\eta^t)$. The representative household maximization problem is

$$\max_{C,L,B} \sum_t \sum_{\eta^t} \beta^t \pi\left(\eta^t\right) u\left(C\left(\eta^t\right), L\left(\eta^t\right)\right) \tag{2}$$

$$\text{s.t. } P_c(\eta^t)C(\eta^t) + \sum_{\eta^{t+1}} Q(\eta^{t+1}|\eta^t)B(\eta^{t+1}) = B(\eta^t) + W(\eta^t)L(\eta^t) + \Pi(\eta^t), \tag{3}$$

where $B(\eta^{t+1})$ denotes the quantity of bonds that pay one unit of consumption in state η^{t+1} (and zero otherwise) and are priced at $Q(\eta^{t+1})$. The consumption price and wage level are denoted by $P_c(\eta^t)$ and $W(\eta^t)$, respectively. The Home wage is the numeraire. Thus when we discuss prices we are always considering a price relative to the wage. Retail firms are owned by the household and their aggregate profits are denoted by $\Pi(\eta^t)$.

3.3 Consumption producers

The aggregate consumption good is a constant elasticity of substitution (CES) bundle of domestic, D, and imported, I, varieties,

$$\begin{aligned} Y_C(\eta^t) = \Bigg[&(1-\tau_c)^{\frac{1}{\gamma}} \left(\int_0^1 \nu_D(j,\eta^t)^{\frac{1}{\theta}} c_D(j,\eta^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} \\ &+ \tau_c^{\frac{1}{\gamma}} \left(\int_0^1 \nu_I(j,\eta^t)^{\frac{1}{\theta}} c_I(j,\eta^t)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} \Bigg]^{\frac{\gamma}{\gamma-1}}, \end{aligned} \tag{4}$$

where ν_i denotes the demand shock to variety j from source $i \in \{D, I\}$ and c_i denotes the corresponding quantity demanded by the firm. Home bias in the consumption bundle is governed by τ_c. The elasticity parameters θ and γ denote the degree of substitutability within and across domestic and foreign goods, respectively.

The firm chooses quantities of domestic and imported consumption goods, c_D and c_I, to maximize profits,

$$P_C Y_C(\eta^t) - \int_0^1 p_D(j,\eta^t) c_D(j,\eta^t)\, dj - \int_0^1 p_I(j,\eta^t) c_I(j,\eta^t)\, dj, \tag{5}$$

subject to (4). The associated demand functions are

$$c_D(j,\eta^t) = \left(\frac{p_D(j,\eta^t)}{P_D(\eta^t)}\right)^{-\theta}\left(\frac{P_D(\eta^t)}{P_C(\eta^t)}\right)^{-\gamma}\nu_D(j,\eta^t)(1-\tau_C)Y_C(\eta^t) \tag{6}$$

$$c_I(j,\eta^t) = \left(\frac{p_I(j,\eta^t)}{P_I(\eta^t)}\right)^{-\theta}\left(\frac{P_I(\eta^t)}{P_C(\eta^t)}\right)^{-\gamma}\nu_I(j,\eta^t)\tau_C Y_C(\eta^t), \tag{7}$$

where $P_D(\eta^t)$ is the price of the bundle of domestic varieties and $P_I(\eta^t)$ is the price of the bundle of imported varieties, defined by

$$P_D(\eta^t)^{1-\theta} = \int_0^1 \nu_D(j,\eta^t)p_D(j,\eta^t)^{1-\theta}dj \tag{8}$$

$$P_I(\eta^t)^{1-\theta} = \int_0^1 \nu_I(j,\eta^t)p_I(j,\eta^t)^{1-\theta}dj. \tag{9}$$

The aggregate price $P_C(\eta^t)$ is a function of the prices of domestic and imported bundles,

$$P_C(\eta^t)^{1-\gamma} = (1-\tau_C)P_D(\eta^t)^{1-\gamma} + \tau_C P_I(\eta^t)^{1-\gamma}. \tag{10}$$

3.4 Manufacturing Producers

In each country, there are a continuum of manufacturers that produce a homogeneous good and operate in a perfectly competitive market. These manufacturers are modeled as representative firms. They combine local labor and intermediate goods to produce,

$$M(\eta^t) = L_p(\eta^t)^{1-\alpha}Y_M(\eta^t)^{\alpha}, \tag{11}$$

where L_p denotes labor used production. The bundle of intermediate goods used in manufacturing production is Y_M and is a CES bundle of the varieties of intermediates,

$$Y_M(\eta^t) = \Bigg[(1-\tau_m)^{\frac{1}{\gamma}}\left(\int_0^1 \nu_D(j,\eta^t)^{\frac{1}{\theta}}m_D(j,\eta^t)^{\frac{\theta-1}{\theta}}dj\right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}} + \tau_m^{\frac{1}{\gamma}}\left(\int_0^1 \nu_I(j,\eta^t)^{\frac{1}{\theta}}m_I(j,\eta^t)^{\frac{\theta-1}{\theta}}dj\right)^{\frac{\theta}{\theta-1}\frac{\gamma-1}{\gamma}}\Bigg]^{\frac{\gamma}{\gamma-1}}, \tag{12}$$

where ν_i is the same firm-specific demand shock in (4). The quantity of variety j used to produce manufactured goods is denoted by m_i. The home bias in intermediate good use is captured by τ_m. The differential home bias in consumption and manufacturing allows us to make trade less intensive in consumption goods, as observed in the data (Boileau, 1999; Miroudot et al., 2009). Note that the home bias is the only difference in the consumption and manufacturing production technologies.

Manufacturers take the wage, W, and the price of intermediates, P_M, as given. The manufacturer's problem yield's demand functions for each intermediate variety,

$$m_D(j,\eta^t) = \left(\frac{p_D(j,\eta^t)}{P_D(\eta^t)}\right)^{-\theta}\left(\frac{P_D(\eta^t)}{P_M(\eta^t)}\right)^{-\gamma}\nu_D(j,\eta^t)(1-\tau_M)Y_M \tag{13}$$

$$m_I(j,\eta^t) = \left(\frac{p_I(j,\eta^t)}{P_I(\eta^t)}\right)^{-\theta}\left(\frac{P_I(\eta^t)}{P_M(\eta^t)}\right)^{-\gamma}\nu_I(j,\eta^t)\tau_M Y_M. \tag{14}$$

The CES price index for the intermediate input is

$$P_M(\eta^t)^{1-\gamma} = (1-\tau_M)P_D(\eta^t)^{1-\gamma} + \tau_M P_I(\eta^t)^{1-\gamma}. \tag{15}$$

3.5 Retailers

Each country has two retail sectors, one for domestic goods and another for imported goods. Each sector consists of a unit mass of firms that sell differentiated products. The firms face stochastic, idiosyncratic demand, $\nu(j,\eta^t)$, and hold inventories, s. In each period, firms decide how much input, z, to order and what price, p, to charge for their differentiated variety.

Input orders are subject to delay, as defined in (1). The timing is as follows: firms observe their demand and place their input orders, they observe whether the inputs arrive in the current period, and finally, they set prices. Firms pay a fixed cost ϕ_D or ϕ_I if they order a positive quantity of inputs. Thus, firms have an incentive to order less frequently and save inputs in inventories to meet demand. Inventories of firms selling domestically-sourced goods $s_D(j,\eta^t)$ (and for imported-good firms, $s_I(j,\eta^t)$) depreciate at rate δ. Goods that were ordered but not delivered in the current period also depreciate at the same rate—they depreciate in transit.

A firm's sales are limited by the stock of goods on hand, so total sales are restricted to sales of inventories and any goods that arrive in the current period. If demand exceeds this value, the firm sells all of its goods on hand and carries zero inventories into the next period. Ending-period inventories are carried over to the next period net of depreciation.

In the following, we present the problem of the home country's domestic-good retailers. The problems for the home country's imported-good retailers and the foreign country's retailers are analogous. For simplicity, we suppress the notation for the aggregate state. Given the firm's beginning of period inventory and demand, s and ν, the firm's value is

$$V_D(s,\nu) = \max\left\{V_D^N(s,\nu), J_D(s,\nu) - W\phi_D\right\}, \tag{16}$$

where V_D^N is the value of the firm if it does not place an order for inputs and $J_D(s,\nu)$ is the gross value of the firm if it places an order for inputs. If the firm places an order, it pays the fixed cost ϕ_D, which is denominated in units of labor.

If the firm does not place an order, it chooses its price and quantities to sell to the manufacturing and consumption-good firms. These quantities are constrained by the inventories on hand,

$$V_D^N(s,\nu) = \max_{p,c,m} p\left[c\left(p,\nu\right) + m\left(p,\nu\right)\right] + \mathbb{E}_{\nu'} QV_D(s',\nu') \tag{17}$$

$$\text{s.t.} \quad s \geq c\left(p,\nu\right) + m\left(p,\nu\right) \tag{18}$$

$$s' = (1-\delta)\left[s - c\left(p,\nu\right) - m\left(p,\nu\right)\right]. \tag{19}$$

If the firm places an order, either the inputs arrive in the current period or the next. If the inputs did not arrive in the current period, the value of the firm is

$$V_D^O(s,\nu,z) = \max_{p,c,m} p\left[c\left(p,\nu\right), m\left(p,\nu\right)\right] + \mathbb{E}_{\nu'} QV_D(s',\nu') \tag{20}$$

$$\text{s.t.} \quad s \geq c\left(p,\nu\right) + m\left(p,\nu\right) \tag{21}$$

$$s' = (1-\delta)\left[s + z - c\left(p,\nu\right) - m\left(p,\nu\right)\right]. \tag{22}$$

Notice that the inputs, z, do not appear in the stockout constraint (21) and deterministically arrive in the next period. If the inputs arrive in the current period, the firm's value is the same as that defined in (17) except its inventories are $s + z$. The value of the firm when it places an order is

$$J_D(s, \nu) = \max_z \; -p^m z + (1 - \mu_D)V_D^N(s + z, \nu) + \mu_D V_D^O(s, \nu, z). \tag{23}$$

The solution to these problems takes the form of an "sS rule," where firms place orders when inventories have fallen to low enough levels. Conditional on reordering, the firm places an order to equate the expected marginal value of a unit of inventory in the next period to the marginal price of the input today

$$\mathop{\mathbb{E}}_{\nu',\eta',\mu_D} Q(\eta'|\eta)V_{D1}(s', \nu'; \eta') = p^m(\eta), \tag{24}$$

where V_{D1} is the derivative of the value function with respect to the inventory level and the expectation is over tomorrow's aggregate and idiosyncratic shocks and today's delivery shock.

The firm's pricing rule depends on the level of current inventories and demand. When firms are constrained by their stock of inventories they set a price to sell everything on hand. When they are unconstrained either because they received a delivery or did not place an order, the pricing function has the usual constant markup specification common to CES demand formulations,

$$p(s, \nu) = \frac{\theta}{\theta - 1} \mathop{\mathbb{E}}_{\nu',\eta'} Q(\eta'|\eta)V_{D1}(s', \nu'; \eta'). \tag{25}$$

Notice that the markup is over the discounted marginal value of inventories tomorrow. If the firm makes a sale today, it begins the next period with fewer inventories. Only when the firm's order is delivered today is the price a markup over the current price, p^m.

3.6 Equilibrium

An equilibrium is a set of quantities: $C(\eta^t)$, $B(\eta^t)$, $L(\eta^t)$, $M(\eta^t)$, $\Pi(\eta^t)$, $L_p(\eta^t)$, $m_D(j,\eta^t)$, $m_I(j,\eta^t)$, $c_D(j,\eta^t)$, $c_I(j,\eta^t)$, $s_I(j,\eta^t)$, $s_D(j,\eta^t)$, $z_I(j,\eta^t)$, $z_D(j,\eta^t)$, prices: $p^m(\eta^t)$, $W(\eta^t)$, $Q(\eta^{t+1}|\eta^t)$, $p_I(j,\eta^t)$, $p_D(j,\eta^t)$, for $t = 0,\dots,\infty$ and $j \in [0,1]$ and value functions for Home and Foreign, such that

1. Given prices, allocations are the solutions to the households', consumption-good firm, manufacturing-good firm, and the retail firms' optimization problems in each country.

2. The consumption-, and retail-good markets clear in each country.

3. The manufacturing-good markets clear in each country. The supply of the manufactured good produced in each country is sold both domestically and exported,

$$M(\eta^t) = \int_0^1 z_D(j,\eta^t)dj + \int_0^1 z_I^*(j,\eta^t)dj \tag{26}$$

$$M^*(\eta^t) = \int_0^1 z_D^*(j,\eta^t)dj + \int_0^1 z_I(j,\eta^t)dj. \tag{27}$$

   where $z_i(j,\eta^t)$ denotes the intermediate good orders by retailer j of type $i \in \{D, I\}$.

4. Inventories are equal to

$$S(\eta^t) = \int_0^1 s_D(j,\eta^t)dj + \int_0^1 s_I(j,\eta^t)dj$$

$$S^*(\eta^t) = \int_0^1 s_D^*(j,\eta^t)dj + \int_0^1 s_I^*(j,\eta^t)dj$$

   where $s_i(j,\eta^t)$ is the end-of-period stock for retailer j of type i, which evolves according to,

$$s_i(j,\eta^t) = (1-\delta)(s_i(j,\eta^{t-1}) + z_i(j,\eta^t) - c_i(j,\eta^t) - m_i(j,\eta^t))$$

5. Labor markets clear in each country. Labor-market clearing in the home country equates labor supply with labor demand from production labor and labor used for

order costs,

$$L(\eta^t) = L_p(\eta^t) + \int_j \phi_D \mathbf{1}_{z_D(j,\eta^t)} dj + \int_j \phi_I \mathbf{1}_{z_I(j,\eta^t)} dj, \tag{28}$$

where $\mathbf{1}_{z_D(j,\eta^t)}$ is equal to one when firm j places an order and zero otherwise.

6. Bonds are in zero net supply, i.e. $B(\eta^t) + B^*(\eta^t) = 0$ for all η^t.

3.7 Decisions rules in and out of steady state

In figure 8(a) we plot the retailer's ordering rule, as a function of inventory levels, for the firm with the median demand shock. Fixed ordering costs imply that firms only order when inventories fall below a threshold. The importing firm, which faces a higher fixed cost, orders at a lower threshold and places a larger order. Notice that below the order threshold that the amount ordered falls with the level of inventory as firms can meet some of the current demand out of its current order if it is delivered. Owing to the different delivery times, this option is more valuable for domestic than importing firms and leads to a steeper drop in purchases with inventories.

In figures 8(b) and 8(d) we plot the steady-state distribution of inventories and the ordering hazard. The domestic retailers order more frequently and face shorter lead times, so the inventory distribution for domestic firms is smaller and has less variance than the importing retailers.

In figure 8(c) we plot the retailer's pricing, as a function of inventory level, in the steady state, for the median demand shock. Two functions are plotted. The first is the price when the firm's shipment arrives in the period. The second is the price when the firm's order is delayed. When the firm does not order (to the right of the order threshold) the two are identical and falling with the level of inventories. If the firm orders and the goods arrive in the period, the firm's price falls slightly with the inventory level but is very close to a constant markup over p_m. If the order does not arrive, the firm sets its price to stockout and the price function follows the inverse demand function. Notice that in the delayed delivery case, the price of imported goods is identical to the domestic price but otherwise it is higher owing to the larger logistic costs increasing the marginal value of imported inventories relative to domestic inventories.

In figure 8(a), we plot the change in the importing retailer's ordering rule following a persistent aggregate shock to the global import delivery times that raise the delivery time from 55 to 90 days (dashed line). There are two main changes along the intensive and extensive margins. First, low-inventory firms reduce their orders as there is no chance of them selling to current customers with inputs purchased in the current period. The size of these orders falls owing to the higher holding costs from the longer delivery time. Second, higher inventory firms start ordering sooner (i.e., the threshold shifts to the right) as firms expect to be unable to meet future demand with a contemporaneous shipment. To avoid being constrained in the future they stock up on inputs today.

4 Quantification

In this section, we describe how we choose parameters for our quantitative analysis. The calibration largely follows the approach in Alessandria et al. (2022), which is primarily focused on understanding the effect of domestic delays in an earlier period (1950–1987) when trade was less important and logistic frictions were larger. Here we calibrate the steady state of a two-country symmetric model to capture key features of the U.S. and ROW economy in the period 2010–2019 as measured in real terms. We abstract from differences in the composition of trade across countries and steady state trade imbalances. As we aim to capture the dynamics of production, inventory investment, input usage, and consumption of goods, we focus on the goods producing sector. The parameter values are summarized in Table 1.

Assigned Parameters. The model is quarterly. Utility is

$$u(C,L) = \frac{C^{1-\sigma}}{1-\sigma} - \chi \frac{L^{1+\frac{1}{\psi}}}{1+\frac{1}{\psi}}. \tag{29}$$

The intertemporal elasticity of substitution, $1/\sigma$, is set to two. The weight on leisure, χ, is set so that households work one-third of their available time. We set the Frisch elasticity to one-half and the discount factor, β, is $0.96^{1/4}$.

In the manufacturing (equations 11 and 12) and consumption-good (4) technologies, we set the elasticity of substitution across varieties, θ, to six to generate a 20 percent gross markup absent an inventory constraint. After accounting for the fixed order costs and inventory holding costs, the net markups are 14 percent. We set the intermediate-good share, α, of manufacturers to 64 percent, to match the intermediates share of gross output in manufacturing. The taste for foreign goods in consumption, τ_c, and manufacturing production, τ_m, are set jointly to generate an exports-to-manufacturing shipments ratio of 30 percent and the share of intermediate goods in total imports of 75 percent.[5]

The Armington elasticity, γ, is a key parameter. Estimates of this parameter vary widely between work in international macro and international trade (Ruhl, 2008) and our model includes elements from both of these literatures. These differences stem in large part from the identification scheme and horizon considered. Following Backus et al. (1994), most authors choose an elasticity 1.5, yet there are good reasons to go with a lower value. Alessandria and Choi (2021) estimates both short-run and long-run Armington elasticities for the United States, accounting for inventory adjustments, and find a quarterly elasticity of 0.2 and a long-run elasticity of 1.1, with about 7 percent of the gap closed per quarter. Heathcote and Perri (2014) show that international business cycles are best explained with an Armington elasticity of about 0.6. Given this range of values, we set the Armington elasticity to 1.1 and provide sensitivity analysis of our results to this parameter. Note that, at the firm level, each wholesale/retail firm is specialized in the distribution of a single input distinguished by source and has no substitution possibilities.[6]

Jointly determined parameters. The remaining parameters are jointly determined so that our model matches key empirical moments from domestic and global supply chains related to frequency, size, and speed of shipments. The ordering fixed costs, ϕ_D and ϕ_I, average order delays, μ_D and μ_I, inventory depreciation rate, δ, and the variance of the idiosyncratic demand-shock process, σ_ν, shape the ordering and inventory behavior in the model. The demand shocks are log normally distributed, and are identically and independently distributed across varieties and time. We set these parameters to match the average restocking times, inventory-purchase ratios, and ordering frequencies in the data.

[5]This division is based on end-use. We follow the convention of Caliendo and Parro (2015) and allocate capital to material input trade.

[6]Boehm et al. (2019) estimate a firm level substitution following the Tōkhu earthquake and find foreign inputs are Leontief with domestic inputs.

Measuring delays is difficult because the ISM data do not allow us to measure the differences between domestic and international transactions. Thus, we cannot determine both μ_D and μ_I from the data. As a starting point, we assume the delay in international shipments is 55 days in order to match the ISM data on production materials.

We target an aggregate inventory to purchases ratio of 1.3 quarters, as it is in the U.S. data.[7] The inventory-purchases ratio of imported goods is twice that of domestic goods, as documented in firm-level data for a range of countries (Alessandria et al., 2010b; Nadais, 2017; Khan and Khederlarian, 2020). From the ordering frequency data, we target that 30 percent of importers order per quarter and domestic buyers order twice as often, in line with the evidence in Alessandria et al. (2010b) and Alessandria and Ruhl (2021).

To match these moments, we set the variance of the demand shocks to be 1.5 and the annual depreciation rate to 20 percent, similar to the value in Richardson (1995). The fixed cost of ordering the domestic good relative to the imported good is critical in determining the ordering frequencies. These parameters imply that the fixed costs are 1.3 percent and 15.9 percent of the average quarterly revenues for domestic and imported goods buyers, respectively. Given our targets, the probability of receiving the domestic good in the current quarter is calibrated to get an average domestic delay of 35 days. In total, the expenditure-weighted delay is 41 days so that around 55 percent of inputs are received in the period they are ordered.

5 Aggregate effects of transitory delays

In this section, we illustrate how the aggregate economy responds to an unanticipated exogenous, temporary increase in the delivery time for international goods. We also explore how increases in delivery time affect the economy when inventories are low, consumption is subsidized, or employment is discouraged (e.g., for public health reasons). All of the shocks we consider are AR(1) with a quarterly persistence of 0.75, unless otherwise noted. We continue to study a symmetric model, so the shocks are global and hit each country identically. We study the transition following these shocks from the non-stochastic steady state.

[7] In our model, all inventories are held by the retail/wholesale sector, while in reality, inventories are distributed across manufacturers, wholesalers, and retailers. Thus, we use the aggregate inventory-purchases ratio in the data.

5.1 Import Delays

Our baseline analysis considers a shock, ε_{μ_I} to (1), that, on impact, increases international shipping times from 55 days to 90 days. Recall, shipping times from China to the West Coast rose by about 40 days from pre-COVID to the start of 2022. Given the share of trade in total expenditures, this is equivalent to increasing the average shipping delay by about five and a half days. We assume that firms observe the shock *before* deciding to order goods that period. Figure 9 plots the aggregate implications of this shock relative to the steady state.

The direct effect of the international delay is to reduce international trade, although the effects are non-monotonic. In Figure 9(b), we report the path of imports relative to the steady state for two different measures of imports. One (the blue line) counts goods as imports only when they arrive at the importer and therefore excludes any goods that are delayed until they are delivered in the next period. With this measure of imports, the only imports at $t = 0$ are those goods that were ordered in the previous period and were delayed, so trade falls sharply. The other measure (the black line) counts as imports all of a given period's orders whether they arrive or not. Orders increase on impact as firms realize that, over the next few periods, it will take longer than usual to receive goods and therefore buy goods earlier than they otherwise would. This can also be seen in Figure 9(e), in which the labor devoted to ordering costs increases substantially on impact, suggesting an adjustment in the extensive margin of how many firms make orders at time $t = 0$. We saw this ordering behavior in mid-2021, as many firms rushed to obtain goods for the holiday shopping season months earlier than normal because of expected shipping delays. The model predicts that after the first period, orders fall because many firms that want to restock already ordered in $t = 0$ and will get those shipments at $t = 1$ with probability one. In addition to the large amount of past orders, a small fraction of goods ordered in $t = 1$ also arrive in $t = 1$ as the shock to delays is transitory. Thus, ordered goods fall below the steady state and "arrived" goods rise above the steady state, yielding the non-monotonic response of the model. In actual trade data, imports are counted when they reach the port, even if they have not yet reached the manufacturer. Thus, we would expect the response of actual imports to the shock to lie somewhere between our two import measures in Figure 9(b).

The delays in importing foreign goods lead to a substantial contraction in economic activity, with production, consumption (panel a), and employment (panel e) falling sharply on impact. The largest effect is on production, which drops 12 percent on impact. Production rebounds sharply in the second quarter, but still remains 4.5 percent below the initial steady state. The economy gradually converges to the steady state, although one year after the shock, production remains around four percent below its steady-state value. The effect of the shock is smaller for employment than for production because firms can substitute between inputs and labor and, as discussed above, there is a sharp increase in logistic costs related to restocking inventories. The weaker effect of the shock on consumption versus production is related to imports being less important for consumption than for production and the usual consumption smoothing motive. Inventory decumulation cushions the fall in consumption compared to production. Although the effect on consumption is weaker on impact, it is as persistent as the effect on production, as consumers are limited in the goods they can buy until manufacturers have finished restocking inventories.

Given the inability to restock imported goods within the period, more importing firms stockout, which we measure as being constrained by their inventory on hand, as seen in panel (d). By contrast, firms that use domestic goods are little affected, as they face two largely offsetting forces: the lack of imported goods causes substitution in consumption and manufacturing toward domestic goods, but the increase in the price of final goods decreases demand for all goods. As importers stockout, they raise the prices that they charge manufacturers as shown in the green line in panel (f). The increase in the input price then increases the prices for consumption or intermediates. The consumption price increases by about 7.5 percent on impact and remains more than 2 percent above steady state for over two years.

5.2 Shipping delays when inventories are low

We now discuss how the stock of inventories affects the propagation of shocks. A key feature of the aggregate economy since the onset of the pandemic is a very low level of inventories. As we saw, the initial decline in spending early in the pandemic was small compared to the decline in production and met by a reduction in the inventory of goods. When inventories are low, the increase in shipping delays can lead to larger aggregate effects. Moreover, rebuilding stocks can be a source of expansion.

Specifically, we examine the aggregate effects of the import delay when the economy starts with aggregate inventories that are about two-thirds of their steady-state levels. This is done as a surprise reduction in inventories in both countries.[8] To clarify the role of the natural recovery from the low inventories, we plot the path of the economy with low inventories and with low inventories and our import delay shock.

We first describe the effects of having low inventories with no change in delivery times. As Figure 10 shows, with low inventories production is 2.5 percent above the steady state as workers increase hours to rebuild their stocks. Production rises and then falls back gradually to the steady state. A similar but larger dynamic occurs with imports as there is a stronger restocking motive. Despite the production and import boom, consumption falls about 7.5 percent below the steady state and recovers slowly. Firms are investing in rebuilding their inventories. The low stock of inventories leads to a persistent rise in stockouts and a rise in consumption prices.

As Figure 10 shows, the effects of an increase in delivery times are magnified when the economy starts out with lower inventories. Now production drops by 11 percent on impact before recovering sharply and then largely following the path from our baseline case. Notice that controlling for the natural recovery from having low inventories leads to a larger drop in output on impact than in our baseline case (13.5 percent vs 12 percent). Consumption falls by 12 percent on impact, four times more than in the baseline case, and recovers more slowly as rebuilding the inventory stock takes time. Compared to the consumption path with just low inventories, the consumption drop is about 50 percent larger. Many more firms stock out, the shock has a much larger effect of firm inventory levels, and the consumption price increases by more than twice as much. The magnified response arises because more firms find themselves constrained by a lack of inputs making it harder to rebuild these stocks. Adding the delay results in more firms charging higher prices to stock out.

[8] This implies shipments that were expected to arrive in the next period do arrive and that these orders were based on expectations of larger inventories.

5.3 Shipping delays when demand is high

In response to the COVID-induced recession, governments in the United States and the rest of the world increased unemployment benefits, sent checks to households, and made generous loans to businesses. These programs, coupled with increased savings during lockdowns led to strong consumption growth starting in the summer of 2020. In our model, an increase in delays decreases consumption. In this experiment, we consider a demand shock that increases consumption concurrently with the delay shocks.

To capture these features, we modify the household's budget constraint to include a proportional consumption subsidy, τ, that is financed by a lump-sum tax, $T(\eta^t)$. In the steady state, the consumption subsidy is zero. Our experiment considers a transitory shock to τ that lowers the cost of consumption goods by five percent and then mean reverts.

$$\tau(\eta^t)P_c(\eta^t)C(\eta^t) + \sum_{\eta^{t+1}} Q(\eta^{t+1}|\eta^t)B(\eta^{t+1}) = B(\eta^t) + W(\eta^t)L(\eta^t) + \Pi(\eta^t) + T(\eta^t), \quad (30)$$

Our consumption subsidy cushions the fall in consumption, as seen in Figure 11. The extra consumption is primarily accomplished through a much larger draw down of inventories and slightly more production. The price increase is larger as more firms' sales are constrained by their current stock of inventory. Owing to the larger draw on inventories and longer restocking period, prices are persistently elevated.

5.4 Labor supply shock

To capture the lockdowns and the reduction in labor supply during COVID, we introduce a shock to the disutility of working. Specifically, we introduce a transitory shock to the weight on leisure, χ_t. We let the taste for leisure rise by 5 percent leading workers to work less. In this case, manufacturers struggle not only to get physical inputs because of the delay but also lose workers and cannot substitute toward labor to make up for the lack of goods. In Figure 12, we see that manufacturing production falls much more relative to the baseline case. Consumption falls both because fewer manufactured goods are available and because households value it less than leisure. Because of the decreased demand for goods, stockouts and consumption prices are relatively unaffected by the added shortage in labor.

6 A fitting exercise

In this section we introduce several contemporaneous shocks into the model to account for key features of the U.S. and global economy from the end of 2019 to middle of 2022. We allow these shocks to differ in the United States and the ROW and fit them to the data. We then eliminate the changes in delivery times to decompose the contribution of various supply chain disruptions to the dynamics of the aggregate economy. We find that shipping delays were a drag on production in 2021 and 2022 and owing to their elevated levels, will continue to be a drag on economic activity and source of elevated prices through 2023.

We fit the model to the data with the three types of shocks described earlier: restocking delays, labor supply, and consumption subsidies. Save for the import and domestic delay shocks, we allow these shocks to be asymmetric to capture differences in economic activity across country. We have 6 shocks and each shock is assumed to follow an AR1 process with a persistence of 0.75.

We assume the economy is in steady state in 2019Q4 and then recover a sequence of unanticipated shocks that can account for the dynamics of several key macroeconomic variables from 2020Q1 to 2022Q2.[9] We choose these shocks to match the industrial production in the U.S. and the ROW, the U.S. trade balance as a share of trade and U.S. consumption of goods. We do not target trade owing to the measurement issues outlined earlier. The supply chain shocks are chosen to match evidence on delays at home and abroad. Specifically, we use the ISM production delay series to measure delays on domestic deliveries and the change in shipping times between the U.S. and China to measure import delays. Figure 15 plots the path of delays (targeted), stimulus, and disutility of labor. Owing to the different production and public health responses, we recover larger and more persistent stimulus and labor supply shocks in the U.S. than the ROW.

In figure 16 we plot our targeted series (panels a–d) and several additional untargeted series on sales, trade, inventory, and the consumer price (panels e–h) in the U.S. for our target period and an extra year. The model hits the six series exactly and captures some

[9] Given the complexity of such a fitting exercise with our non-linear model, we take a linear approximation of the model around the steady state. We then use these the linear decision rules to recover the combination of shocks that fits the model the data. This is a variation of the approach of Boppart et al. (2018).

aspects of the untargeted series. Business sales of goods rebounds a bit slower than in the data. International trade recovers more slowly than in the data initially but exceeds actual trade flows by the end of 2021. The model predicts a larger inventory draw-down in 2020 and a more robust restocking through 2022. And finally, the price of consumption goods in the U.S. rises considerably more than the data, with the model predicting prices that are up nearly 40 percent by the end of 2021 compared to about 8 percent in the data. All series mean revert as the shock dissipates, but remain away from the steady state.

We next consider the aggregate effects of eliminating each of the supply delays. Figure 18 plots the change in each variable from the path in our benchmark model and economy when we eliminate the specific delay. For the U.S., domestic delays generally have the biggest effects since they are large and hit a larger part of the economy. By 2022Q2, we estimate they reduce industrial production by as much as 8 percent. These delays have decreased inventory holdings by as much as 20 percent and increased prices by as much as 20 percent. Given home bias, delays in the ROW on domestic transactions have smaller effects in the United States. Delays on foreign trade are slightly less of a drag on U.S. industrial production in 2021 and 2022 but were a larger drag on output in the early stages of COVID. Reducing these delays on international trade was a big boost to economic growth in the 2020Q3. While delays on international inputs have been slightly less important than delays in domestic transactions for economic activity, they are considerably less important for the rise in consumption prices owing to trade being more intensive in intermediate inputs.

6.1 Measurement

There are two main challenges in lining the model up with the data. The first, is related to how delays affect measured trade flows and to a lesser extent shipments and inventories. We have already discussed how trade flows depend on whether the delays are before or after the border. Likewise, it is not clear when goods in transit show up in measures of U.S. inventories or at the retail or manufacturing levels. For domestic shipments, whether the delay occurs in shipping from the factory or in delivery is also important for measured shipments.

The second challenge is related to prices, which increase substantially with our delay shocks. Recall that, in the model, firms set prices contingent on deliveries. This leads firms that have their orders delayed to raise their prices to sell all the goods they have on hand, which substantially increases measured prices. Importantly, this price captures the marginal value of the constrained goods to our representative consumer. Alternatively, we could allow firms to set prices prior to delivery, which would lower prices considerably but not change allocations in the delayed delivery state since firms would still be constrained by their stock on hand. Preliminary work with this alternative model has minimal effects on real quantities but brings the brings the model much closer in line with the movements in retail prices. Of course, there are some questions about whether the price series in the data accurately reflect cost of consumption expenditures in the presence of the large and persistent rise in stockouts.[10]

6.2 Expectations

Here we explore how the effects of an increase in restocking delays depend on the process for the delay. We show that when there is an anticipated component to delays they have smaller effects on the economy, as firms prepare by stockpiling. Previous work has shown that this type of anticipatory stockpiling is common when there is a certain or uncertain future shock to trade policy or taxes (Alessandria et al. (2019), Khan and Khederlarian (2021), and Baker et al. (2021)). We then show that our estimates of the contribution of international delays on aggregate outcomes is influenced by the process of the shock.

We consider a smaller but hump-shaped shock with the same discounted change (at the steady state interest rate) as our baseline case.[11] On impact the shock increases delays by about 10 days before rising another 5 days by the 3rd period and then gradually mean reverting. Given that delays are smaller on impact and will get worse before they get better, agents have an opportunity to prepare for the future. As shown in Figure 13, this leads to a minor boost in production on impact as firms stockpile inputs in advance. Production falls gradually and bottoms out 4 percent below the steady state in the fourth quarter. The path after the fourth quarter is similar to the case with an AR(1) shock. Early in the transition, consumption falls by less while prices and stockouts rise by less. The swings in trade are

[10] The BLS imputes the price of goods that are temporarily unavailable using the price of continuously available goods.

[11] In Alessandria et al. (2022), our VAR analysis recovers hump-shaped delay shocks for the U.S. from 1950-1990.

moderated.

We now show that our assumption about the process for the path of delays has modest effects on our estimated contribution of international shipping delay shock. Specifically, we redo our fitting exercise using the AR(2) international delay rather than an AR(1) international delay. Figure 18 compares the effects on key variables of shutting down the international delay shock. With delays that get worse before getting better we find smaller and smoother effects on output and consumption. The peak effect of delays is about 5 percent smaller than our baseline case and comes one period later (in 2022Q2). The effects on consumption are also smaller and peak earlier than in our baseline. There are more substantial differences in the path of trade and inventory. The effects on prices are also about 1/3 smaller along the path. The path of stockouts is largely unchanged though as it is mostly affected by the shock that constrains ordering firms rather than expectations.

7 Final Thoughts

A key feature of the post-COVID economy has been an increase in the time to restock retail and manufacturing inputs. In 2021, these lead times in the U.S. rose to extreme levels unseen for 50 years owing to a confluence of factors. These restocking delays are present in a high rate of retail stockouts. We show how changes in these lead times, both domestic and international, can influence the aggregate economy. In particular, we show that an increase in lead times similar to those from 2020-2022 can be quite contractionary, more so when inventories are already low, and lead to a substantial, but transitory increase in prices. The restocking cycle increases the persistence of these shocks on prices and production.

Our model allows us to decompose the source of fluctuations in aggregate economic activity in the U.S. and the world economy in the 10 quarters from 2020Q1 to 2022Q2. Delays in moving goods appear to have been a substantial drag on economic activity and a source of rising prices. Given the challenges in bringing these delays down, our model suggests these will continue to be an important factor in aggregate economic activity. However, we do find that the unwinding of restocking delays will be a source of expansion of output and reduction in prices, but that the positive effects on output will not offset the waning influence of stimulus from 2021.

Finally, we are agnostic about the source of rising supply chain delays. We are focused on understanding how these delays propagate through the economy. Gaining a deeper understanding of the source of these delays will be important for developing policy responses to address these delays or prevent them in the future.

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8 Figures and Tables

Table 1: Parameter Values and Moments (2010-2019)

Common parameters:		$\beta = 0.96^{1/4}$, $\theta = 6$, $\sigma = 0.5$, $\psi = 0.5$, $\chi = 64.9$		
Moments		Parameters		Baseline
Value added to gross output (mfr)	36%	Input cost share	α	0.64
Imports to manufacturing sales	30%	Import weight consumption	τ_c	0.165
Manufacturing share of imports	75%	Import weight manufactures	τ_m	0.425
Inventory-sales ratio (agg)	1.27	Depreciation (%)	δ	5.5
Inventory-sales ratio (dispersion)	0.72	Demand variance	σ_x^2	1.5
Inventory-sales: importer/domestic	2	Domestic delay	$\bar{\mu}_D$	35 days
Lead Time (ISM)		Import Delay	μ_I	55 days
Order freq (dom)	60%	Fixed order cost† (dom)	ϕ	1.3
Order freq (imp)	33%	Fixed order cost† (imp)	ϕ_I	15.9

†Expressed as share of average revenue.

Figure 1: Manufacturing supplier delivery times

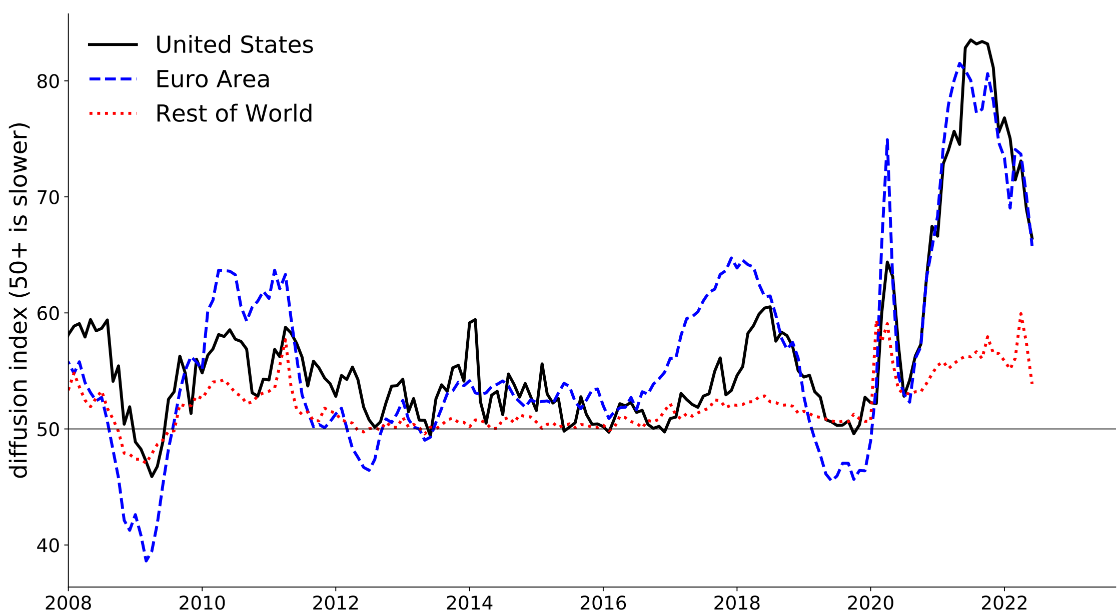


Figure 2: Delivery times

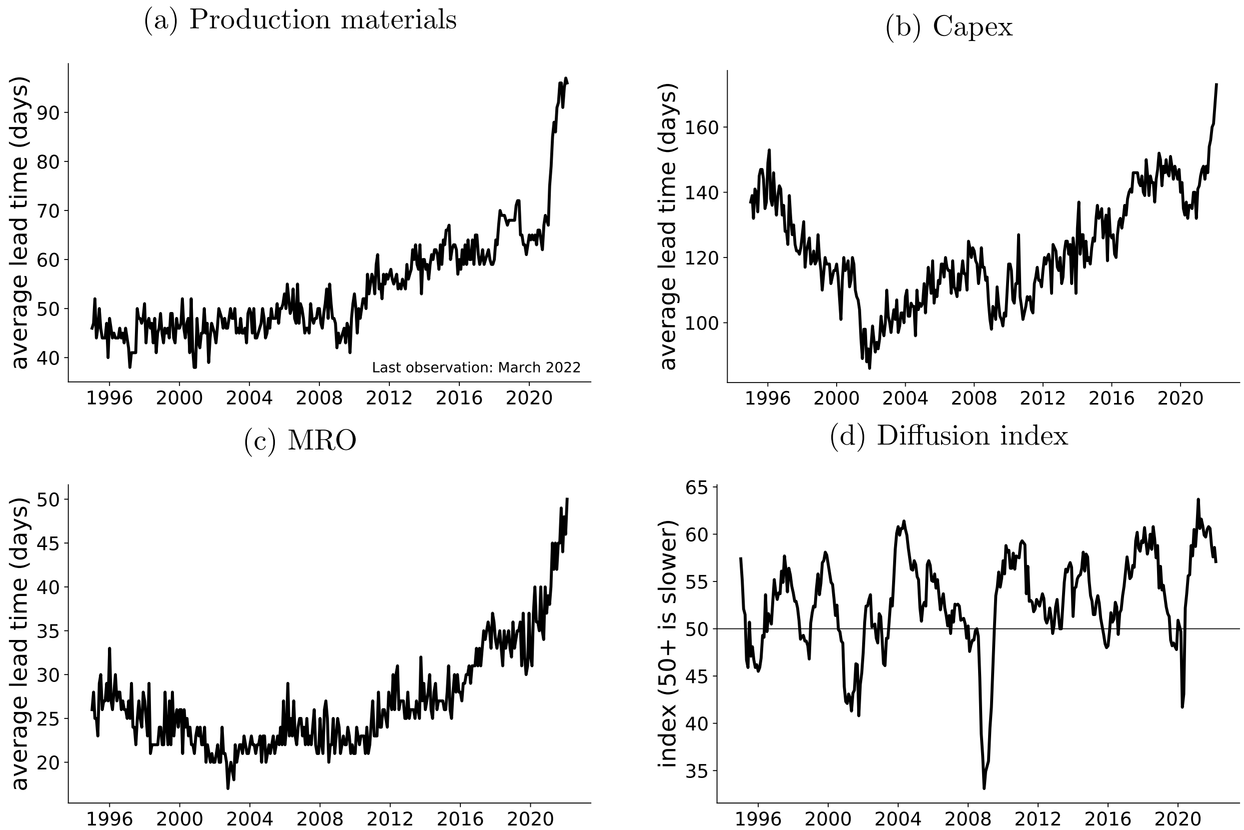


Figure 3: U.S. unfilled orders (nondenfense capital goods, ex. aircraft)

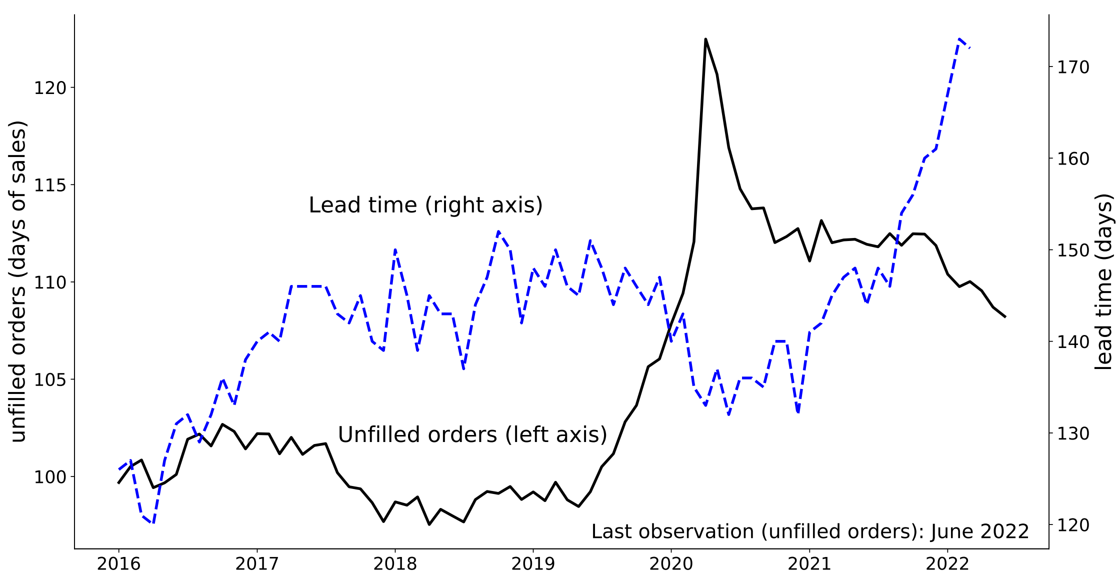


Figure 4: In the last week, did this business have any of the following?

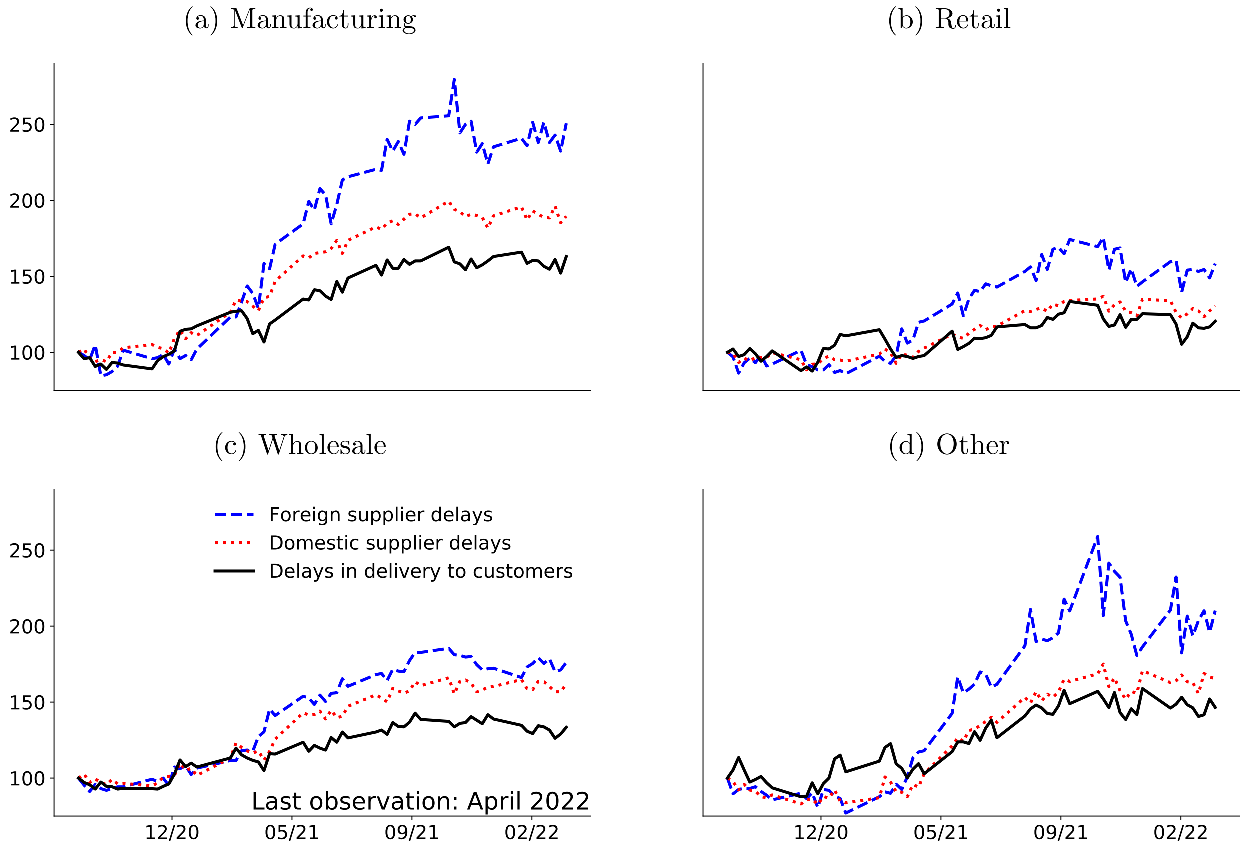
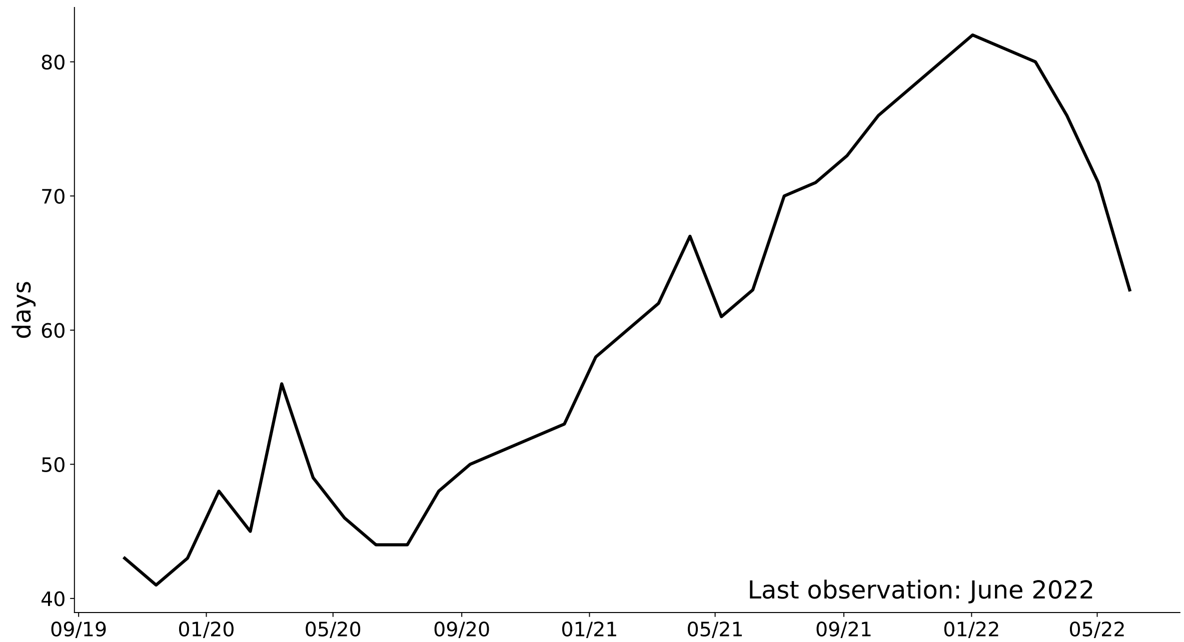


Figure 5: Ocean shipping time to United States from China



Source: Freightos (freightos.com)

Figure 6: U.S. inventory-sales ratio

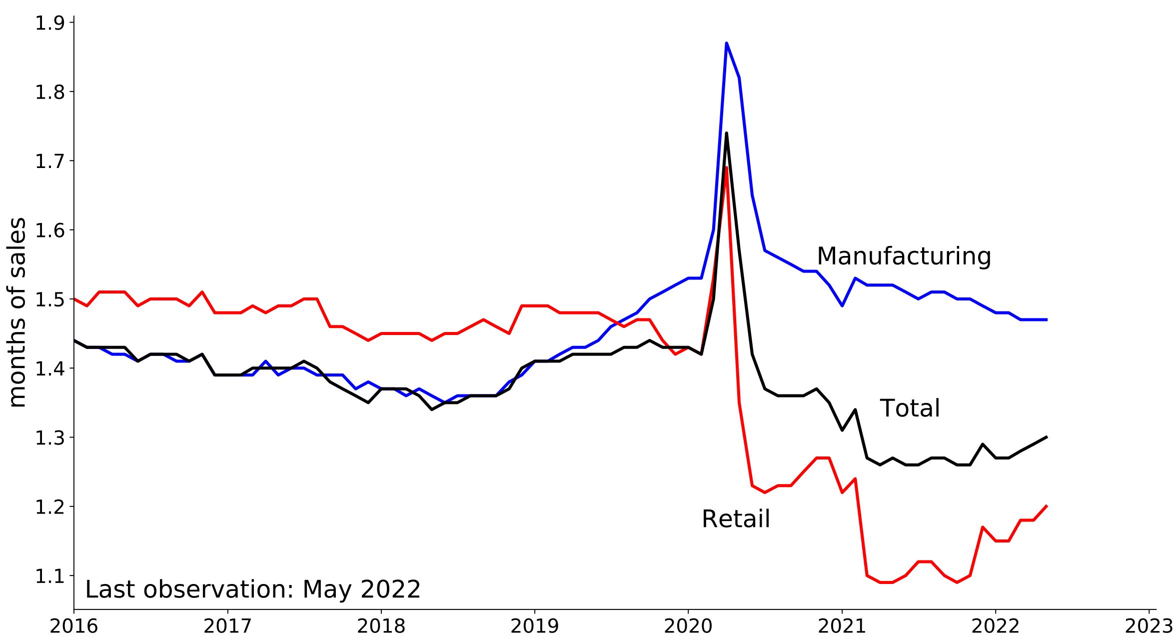


Figure 7: Salient features

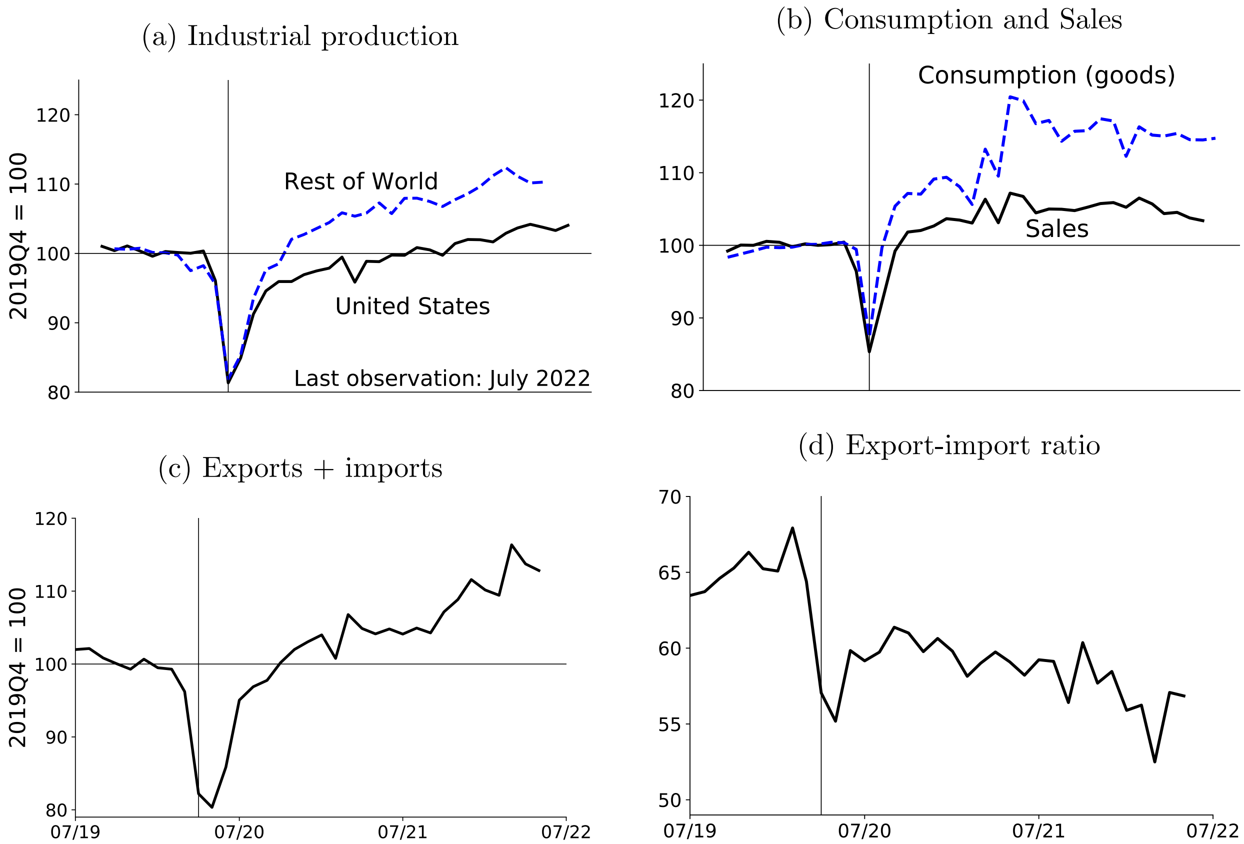
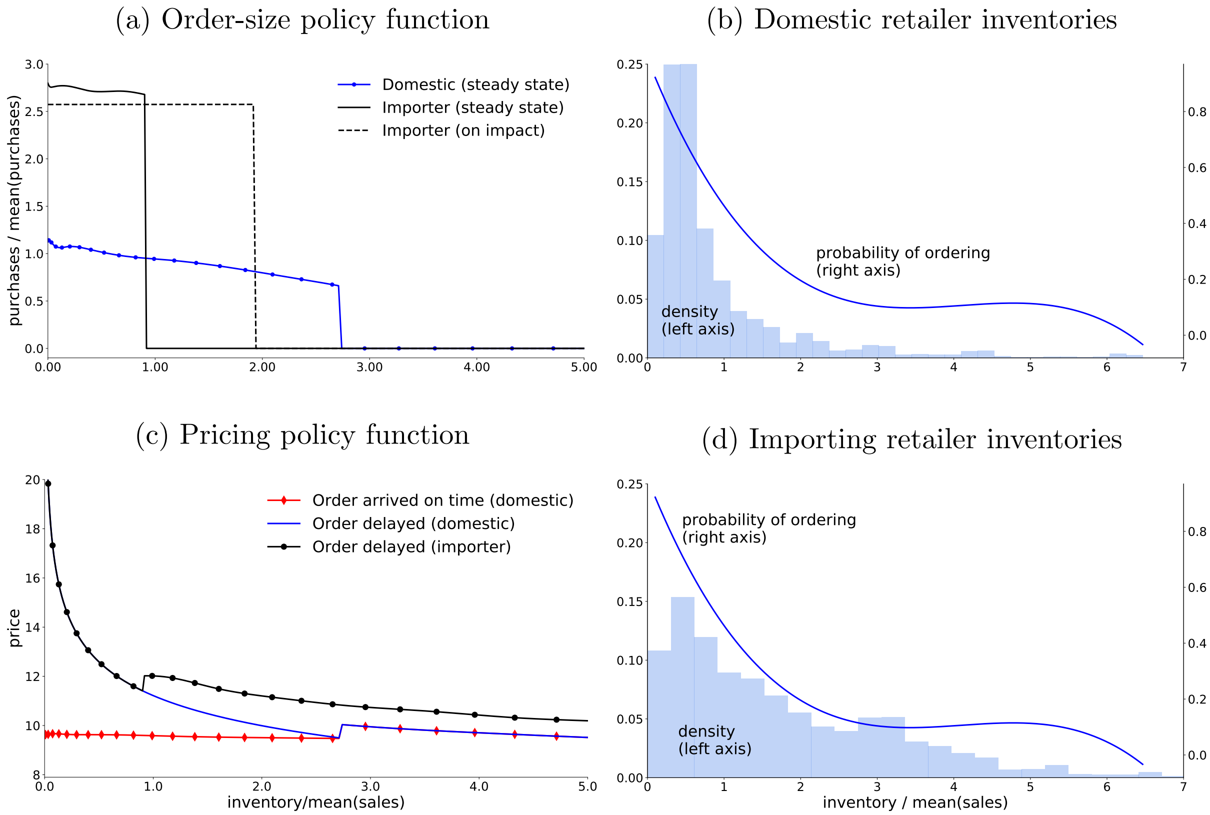


Figure 8: A transitory shock to shipping delays



Notes: The order hazard functions in panels (b) and (d) have been smoothed with a third-order polynomial.

Figure 9: International delay shock

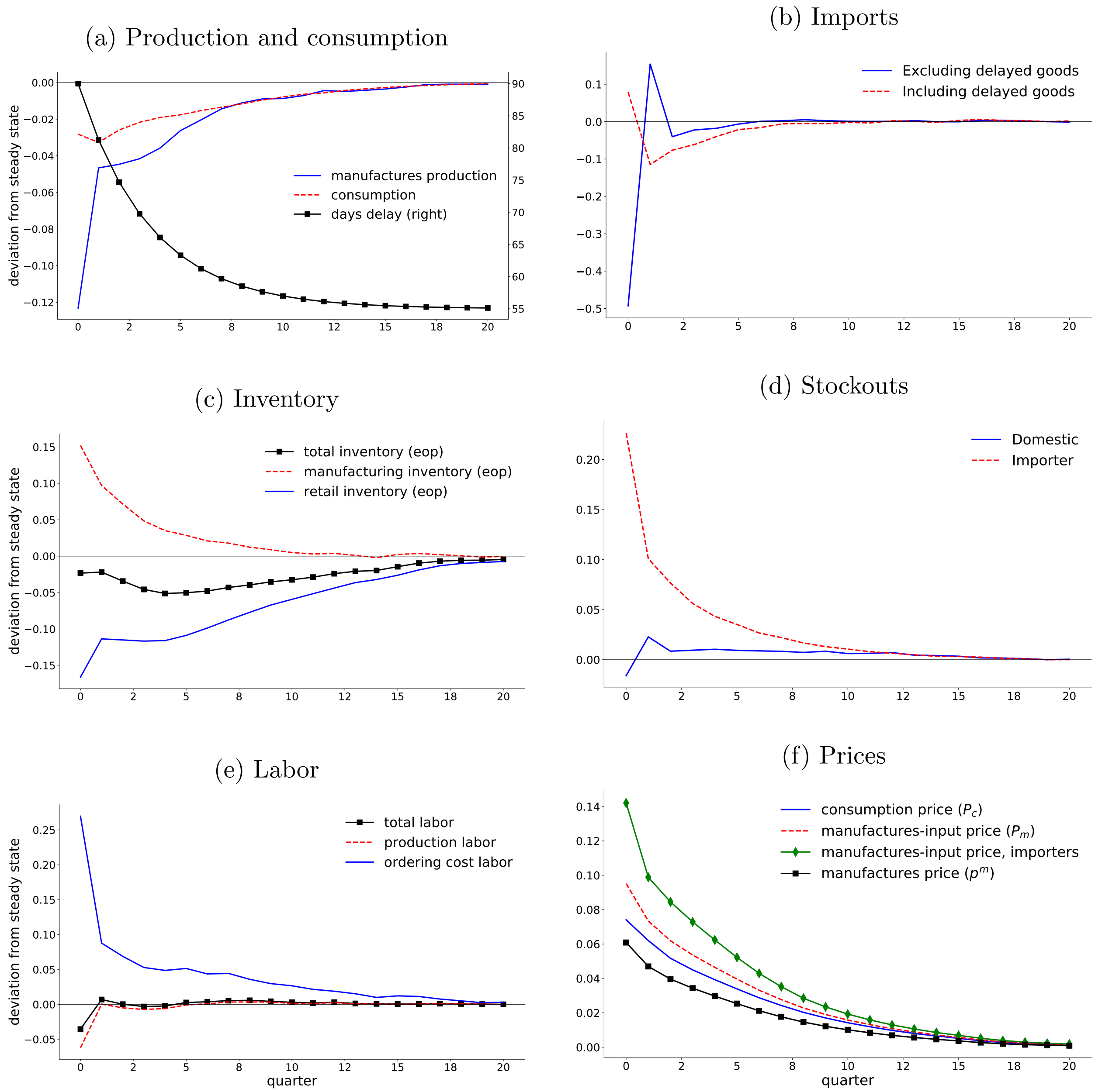


Figure 10: International delays and low inventories

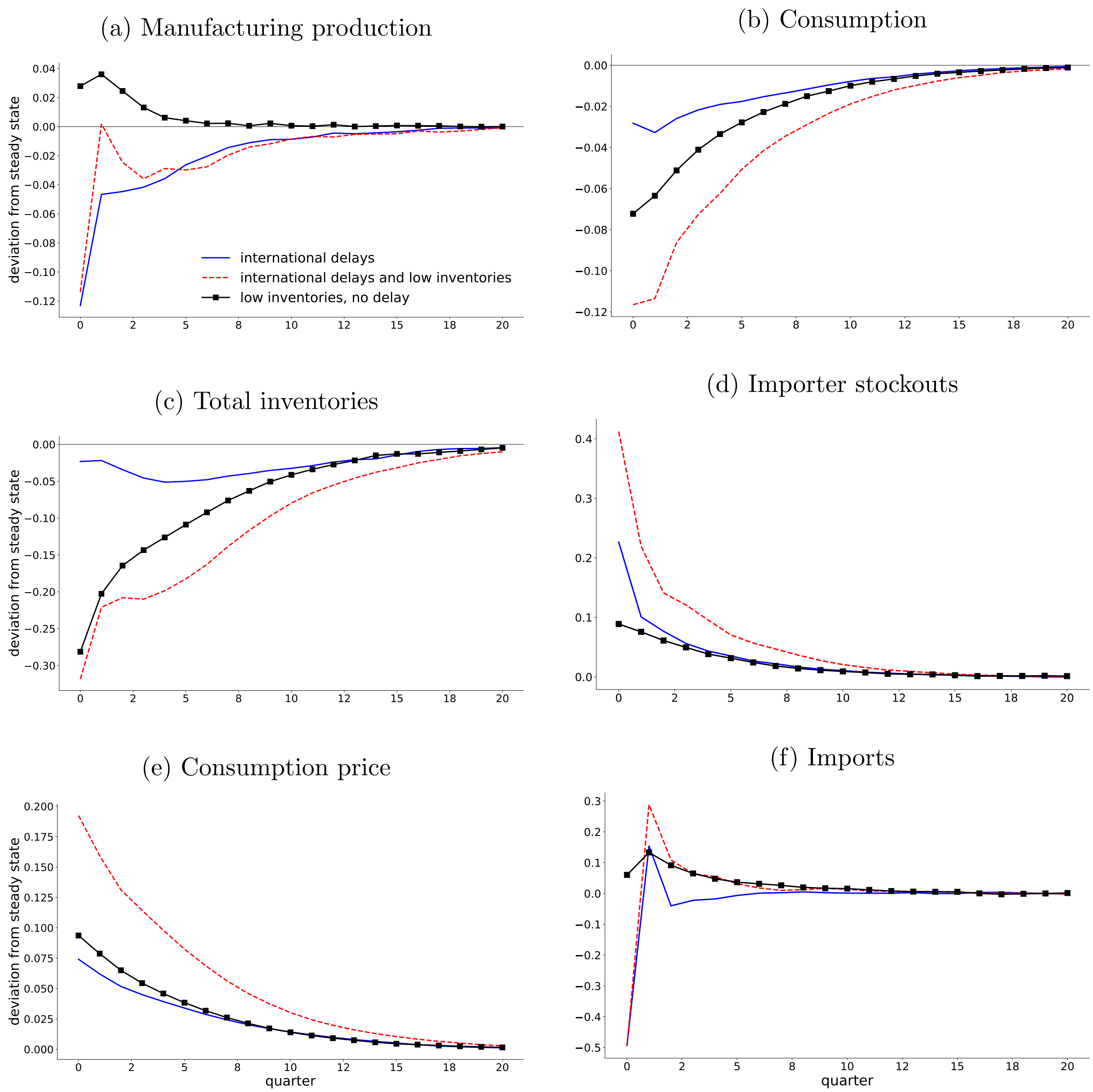


Figure 11: International delay shock and consumption stimulus

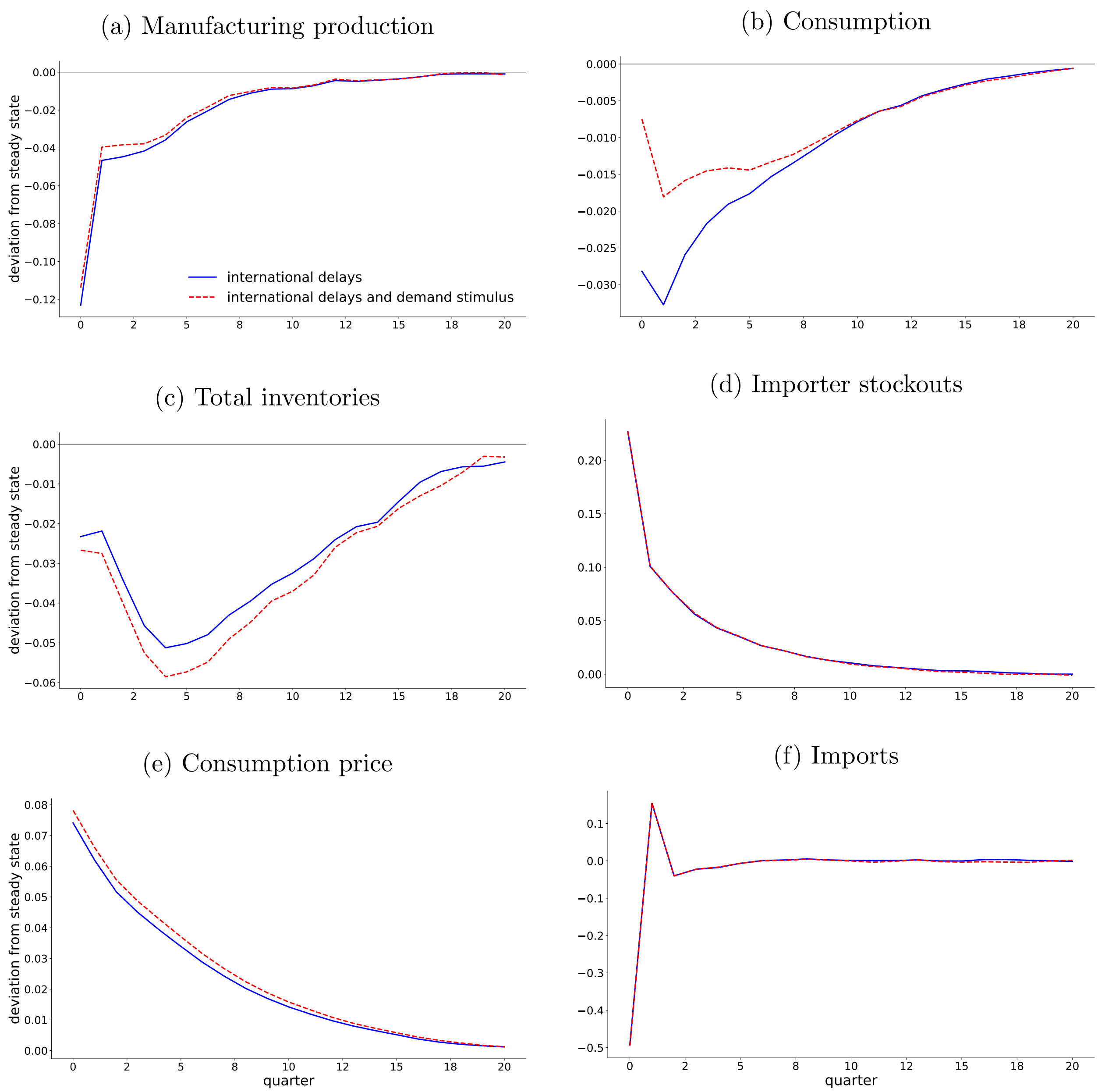


Figure 12: International delay shock and reduced labor supply

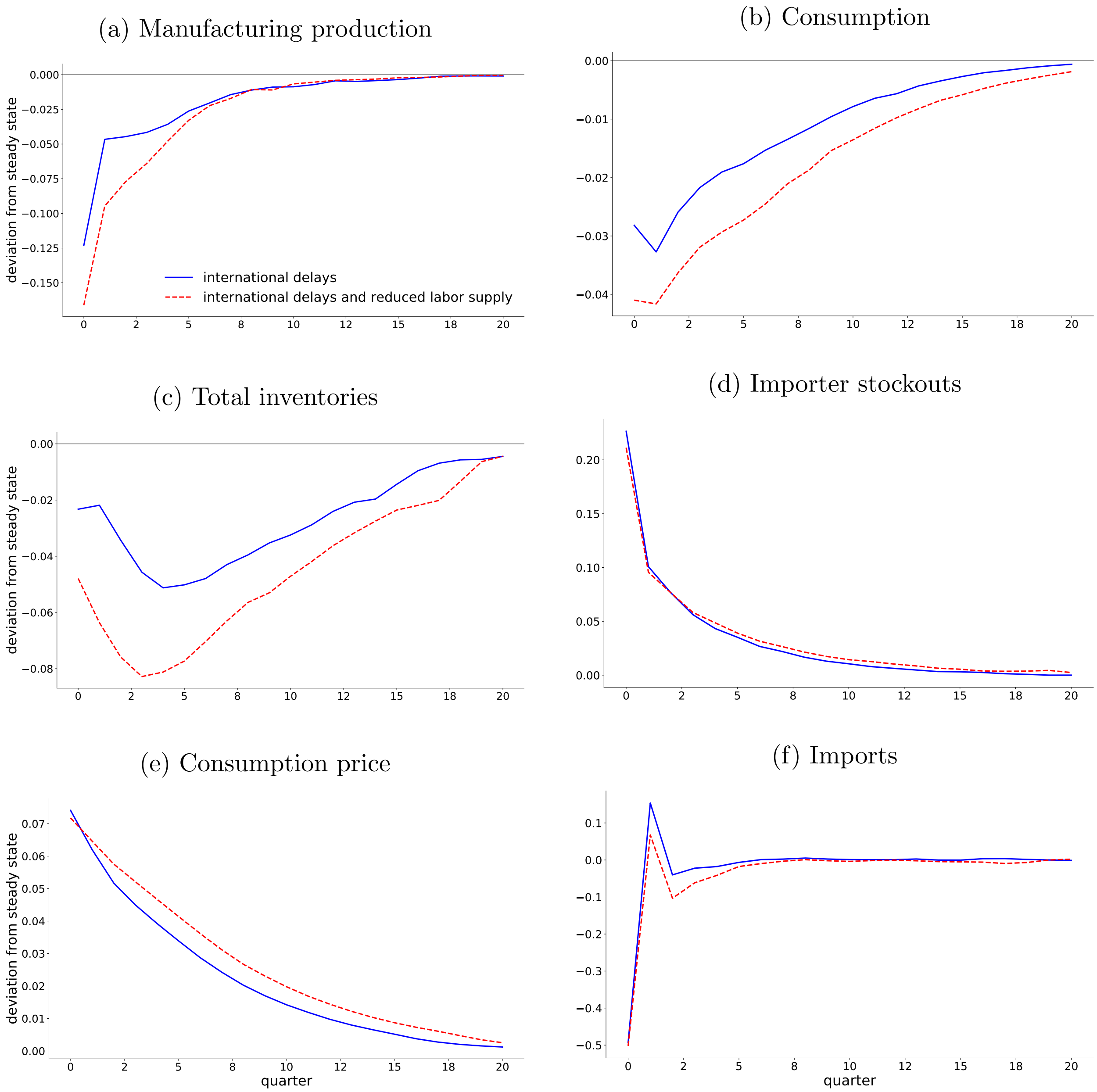


Figure 13: AR(2) delays

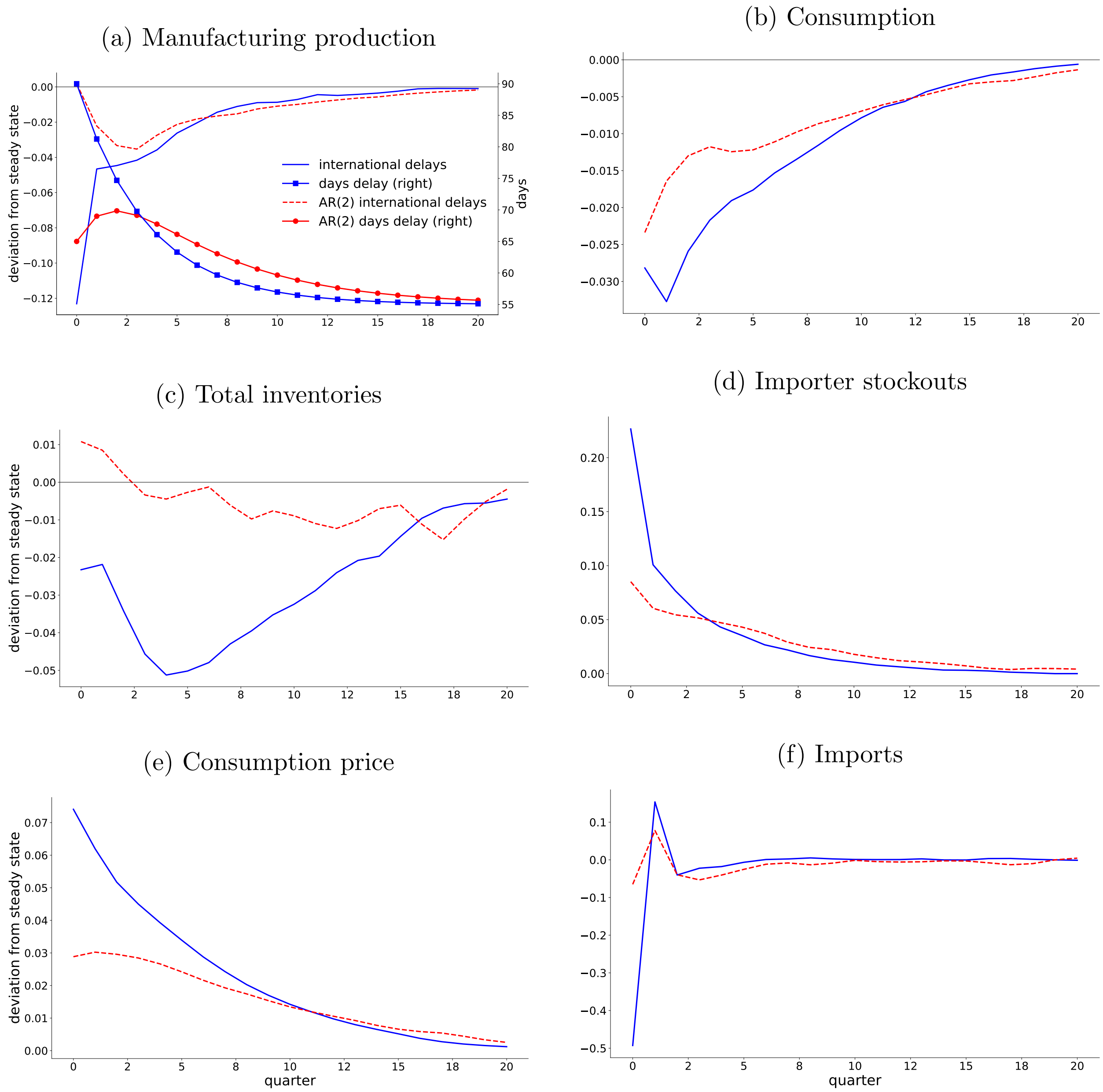


Figure 14: Exogenous shocks

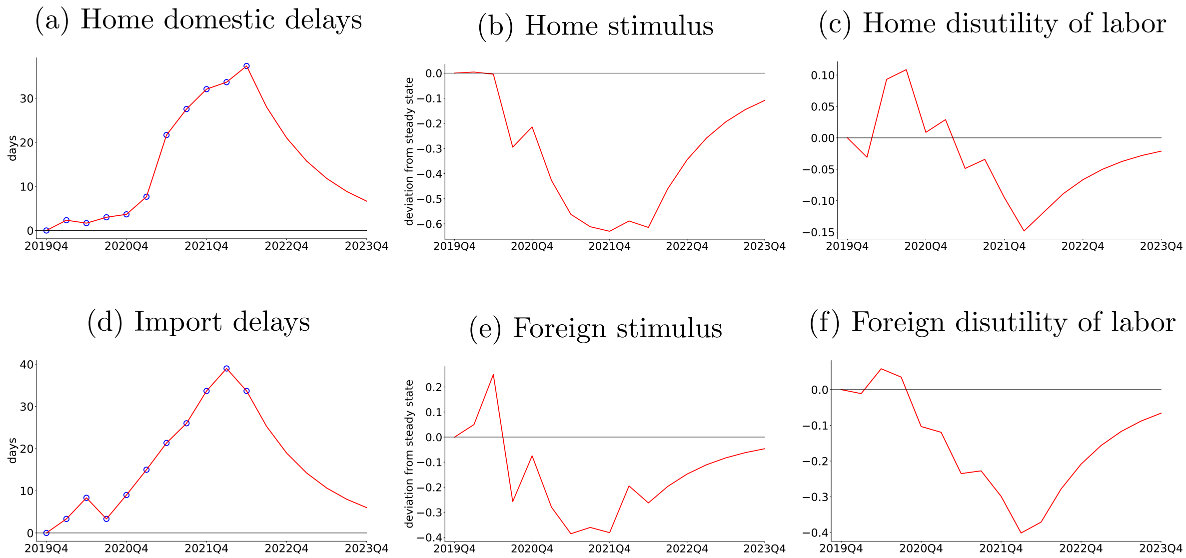


Figure 15: Exogenous shocks: AR(2)

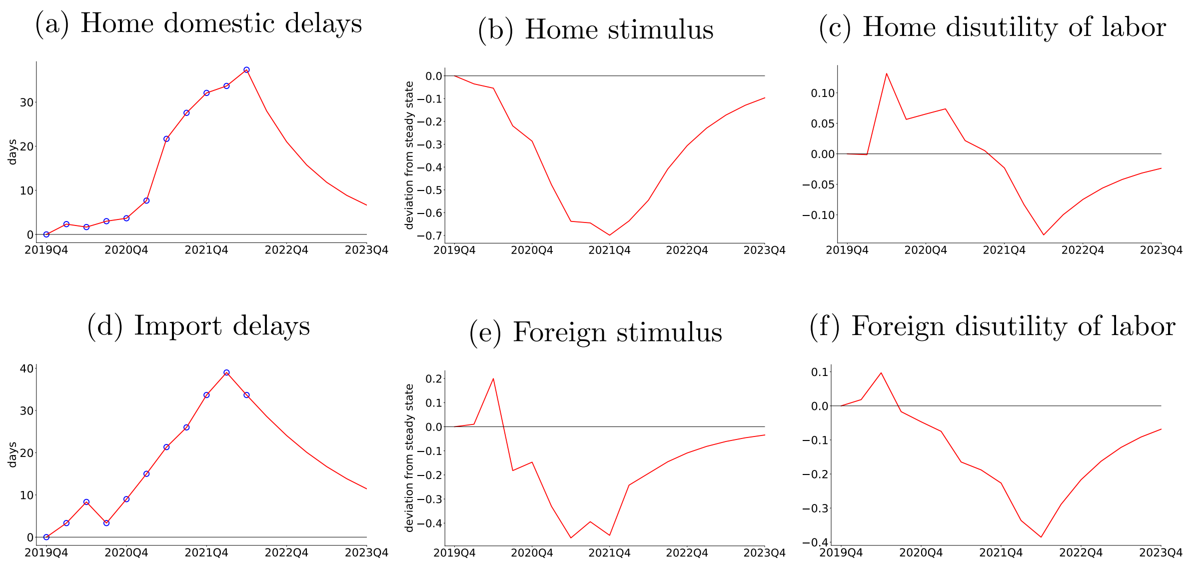


Figure 16: Endogenous variables

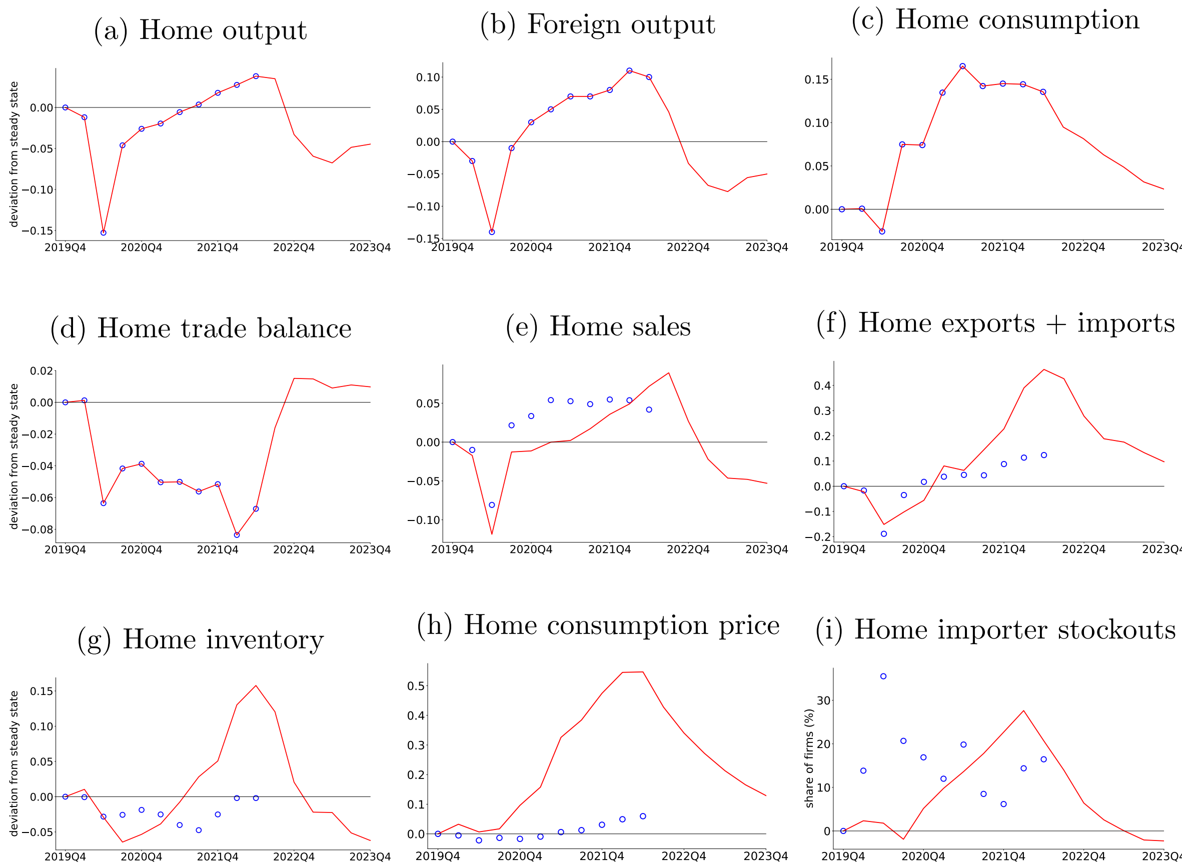


Figure 17: The effect of delays

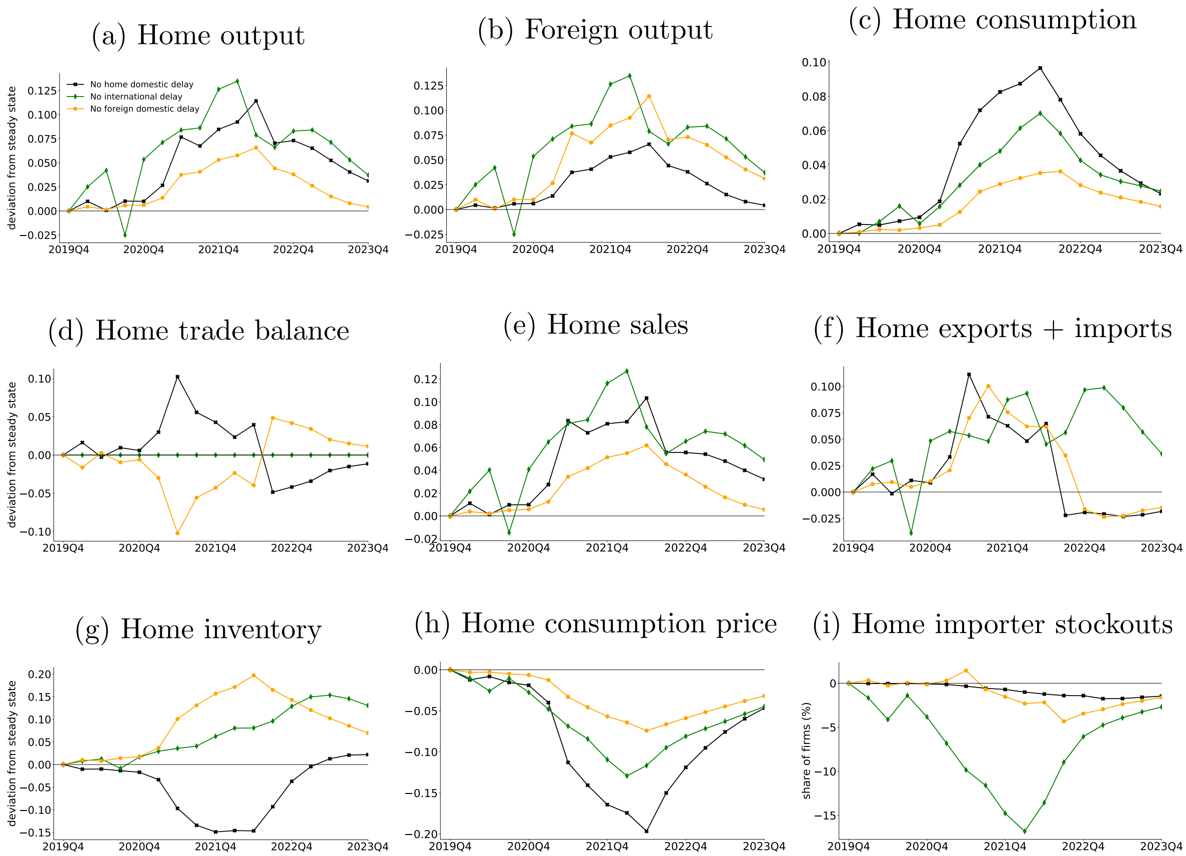


Figure 18: The effect of import delays: AR(1) v AR(2)