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On the Heterogeneous Welfare Gains and Losses from Trade[1]

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[PRELIMINARY AND INCOMPLETE]

Abstract

How are the gains and losses from trade distributed across individuals within a country? First, we document that tradable goods and services constitute a larger fraction of expenditures for poor households. Second, we build a trade model with nonhomothetic preferences—to generate the documented relationship between tradable expenditure shares, income, and wealth—and uninsurable earnings risk—to generate heterogeneity in income and wealth. Third, we use the calibrated model to quantify the differential welfare gains and losses from trade along the income and wealth distribution. In a numerical exercise, we permanently reduce trade costs so as to generate a rise in import share of GDP commensurate with that seen in the data from 2001 to 2014. We find that households in the lowest wealth decile experience welfare gains over the transition, measured by permanent consumption equivalents, that are 67 percent larger than those in the highest wealth decile.

Keywords: trade gains, inequality, consumption
JEL classification codes: E21, F10, F13, F62

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1 Introduction

How are the gains and losses from trade distributed across individuals within a country? On one hand, many researchers have argued that increased trade—especially with China—has contributed to the decline in manufacturing jobs in the U.S. over the last two decades. For example, Autor et al. (2013) find that import competition from China has contributed to a quarter of the job losses in U.S. manufacturing from 1990 to 2007. On the other hand, trade can lead to increased efficiency and lower the price of consumption. If tradable goods constitute a larger fraction of consumption expenditures for poor households, then those households may realize disproportionately larger gains from trade. Fewer studies have analyzed how trade, through its effect on the price of tradable goods and services, affects the distribution of welfare gains across income and wealth.

Our paper makes three main contributions to the literature. First, we document that tradable expenditure shares are decreasing in both income and wealth. Second, we build a trade model with uninsurable income risk and nonhomothetic preferences that generates both heterogeneity in income and wealth and the documented relationship between income, wealth, and tradable expenditure shares. While each of these features has been studied in isolation, we are the first to investigate their interaction in the trade literature. Third, we use the calibrated model to quantify the differential welfare gains and losses from trade for households along the income and wealth distribution. While a reduction in trade costs leads to a welfare increase for all households, it is particularly large for the poor.

In the first part of this paper, we document that tradable goods and services constitute a larger fraction of expenditures for poor households. Using the Panel Survey of Income Dynamics and the Consumer Expenditure Survey, we show that households in the lowest wealth decile spend 39 percent of their consumption expenditures on tradable goods, compared to 30 percent for those in the highest wealth decile. Similarly, households in the lowest and highest income deciles spend 37 and 31 percent, respectively, of their consumption expenditures on tradables. These relations are robust to controlling for a variety of household characteristics such as age, household size, education, and homeownership.

Next, we build a model to analyze the heterogeneous impacts of trade along the income and wealth distribution. Specifically, we extend the classic Ricardian model of trade (Dornbusch et al. 1977) in two dimensions. First, households derive utility from the consumption of a nontradable good and a tradable good according to Stone-Geary nonhomothetic preferences so that poor households have a higher tradable expenditure share. Second, we depart from the representative agent framework by introducing households that face uninsurable income risk in each country. In this environment, households must self-insure by accumulating capital, which is produced using a combination of tradable and nontradable goods. We calibrate the model to match features of the income and wealth distribution in the U.S. as well as the relation between tradable consumption shares and wealth that we document in the empirical section.

We use the calibrated model to compute the distribution of welfare gains along a transition from a symmetric steady state equilibrium with high trade costs to one with 8.5 percent lower trade costs. In this exercise, the reduction in trade costs produces a rise in import share from 13 percent to 17 percent, on par with the rise seen in the data since the admission of China into the World Trade Organization in 2001. Using permanent consumption equivalents as the metric of welfare change, we find that welfare gains are significant, averaging 1.89 percent, and that they vary significantly with income and wealth. Households in the lowest wealth decile experience welfare gains that are 67 percent larger than those in the highest wealth decile.

Why do poor households experience larger welfare gains from reducing trade costs? The source of the disparity can be decomposed into three channels. The first is the *expenditure* channel: Lower trade costs lead to a fall in the price of tradable goods.[2] As a result, poor households, which spend a larger share of expenditures on tradable goods, receive larger welfare gains.

Since tradable goods are also an input into capital production, a lower tradable price decreases the price of investment as well. This benefits households with high income and low wealth because they are typically buyers of capital, but harms households with low income and high wealth, which sell capital to smooth consumption. We refer to this as the *investment* channel. A lower investment price makes replacing capital cheaper, reducing

[2] This is consistent with Broda and Romalis (2008), Amiti et al. (2018), Bai and Stumpner (2019), and Jaravel and Sager (2018), who document that increased import competition from China has resulted in lower prices of tradable goods.

depreciation costs. This initially pushes up the net return to capital, leading to capital deepening, which over time also results in a higher wage. This movement in factor prices benefits all households, especially the poor, who derive most of their income from labor—this is the *factor price* channel. Notice that trade benefits wealth-poor households through all three channels.

Our paper is related to several strands of the literature. On the empirical side, our work adds to the literature that documents the heterogeneity in consumption bundles across income groups. This traces back to Engel (1857), who documented that food expenditure shares decrease with income (Engel's law), and Houthakker (1957), who documented that Engel's law applies in many countries and for a broader set of goods than just food. More recently, Boppart (2014) used the Consumer Expenditure Survey to document that low-income households spend larger shares of their expenditures on goods relative to services. We contribute to this literature by demonstrating that Engel's law applies to tradable goods and along the wealth dimension, even after controlling for income and other household characteristics such as age, education, and household size.

Additionally, this paper is related to work that estimates the heterogeneous price effects of trade on households.[3] For example, Broda and Romalis (2008) document that price inflation for households in the lowest income decile has been 7 percentage points smaller than inflation for the highest decile between 1999 and 2005, and that one-third of the relative price drops faced by the poor are associated with rising Chinese imports. Our findings differ from those in Borusyak and Jaravel (2018) and Hottman et al. (2018), who also use the Consumer Expenditure Survey. Borusyak and Jaravel (2018) document that import shares are similar across education groups and income quantiles, while Hottman et al. (2018) estimate a structural model with supplier trade data and find that lower income households experienced the most import price inflation. In contrast to these studies, we examine expenditures on tradable goods, as opposed to expenditures on imported goods. This is an important distinction because changes in trade can have a broad impact on the price of all tradable goods through, for instance, increased competition, as shown in Jaravel and Sager (2018),

[3]Because the expenditure share on tradable goods differs across households, one should expect that trade reforms and their corresponding effects on tradable prices impact households differently.

or through input-output linkages.[4]

On the theoretical side, we build on the Ricardian trade model of Dornbusch et al. (1977) by introducing Stone-Geary nonhomothetic preferences as in Buera and Kaboski (2009), Herrendorf et al. (2013), Uy et al. (2013), and Kehoe et al. (2018), and by introducing households with uninsurable income risk as in Aiyagari (1994), Bewley (1986), Huggett (1993), and Imrohoroğlu (1989).[5]

Our paper is also related to recent works that have quantified the heterogeneous welfare gains and losses from trade.[6] Fajgelbaum and Khandelwal (2016) develop an Armington model with nonhomothetic preferences and exogenous differences in income to compute the heterogeneous welfare effects of trade along the income distribution. Artuç et al. (2010), Caliendo et al. (2019), Dix-Carneiro (2014), Dix-Carneiro and Kovak (2017), Galle et al. (2017), and Kondo (2018) develop trade models with labor market frictions to quantify the heterogeneous effects of trade without savings. Our work is most related to Lyon and Waugh (2019), who also use a Ricardian trade model with uninsurable income risk to study how labor market reallocation frictions affect the gains from trade. We abstract from labor market frictions and instead focus on the heterogeneous impacts of trade through the expenditure, investment, and factor price channels. We find that the differential welfare gains experienced by low- and high-wealth households are similar in magnitude to the those experienced by households in import- and export-exposed labor markets in Lyon and Waugh (2019).[7]

The remainder of the paper is structured as follows. Section 2 documents the relation between tradable expenditure shares and income and wealth. In Section 3, we present a two-country Ricardian model of trade with nonhomothetic preferences and heterogeneous agents that face uninsurable labor income risk. In Section 4, we discuss the calibration of the model and discuss the main quantitative findings. Section 5 concludes by discussing implications and directions for future research.

[4]Because Borusyak and Jaravel (2018) consider direct and indirect imports, they capture some input-output linkages but not pro-competitive effects.

[5]See also Matsuyama (2000), who develops a Ricardian model with nonhomothetic preferences.

[6]Costinot and Rodríguez-Clare (2014) provide an excellent review of this literature.

[7]See also Ferriere et al. (2018) who study the heterogeneous gains from trade in a life-cycle model with skill acquisition.

2 Data

In this section, we use the Panel Survey of Income Dynamics (PSID) and the Consumer Expenditure Survey (CEX) to document the relation between household tradable expenditure shares and disposable labor income and wealth. Our main finding is that tradable expenditure shares are decreasing in both disposable labor income and wealth. The differences are both sizable and statistically significant.

2.1 Description of the data

For the CEX, we have 23,484 household-year observations between 2004 and 2014. Tradable consumption is defined as the sum of the 307 items classified as tradable in Johnson (2017), where an item is tradable if the percentage of total output of that category represented by either exports or imports exceeds 11 percent. Total consumption is defined as the sum of the 568 expenditure items, where we subtract expenditures on mortgage interest, property taxes, and homeowner's and renter's insurance, and in the case of homeowners, we add the self-reported owner's equivalent rent. Total labor income is computed as the sum of household wages and salaries and 50 percent of farm and business income. Next, we construct household disposable labor income as total household labor income plus transfers minus tax liabilities, computed for each household using the TAXSIM tax calculator. For wealth, we use liquid wealth, which is defined as the sum of retirement accounts, checking and savings accounts, and other financial assets.

For the PSID, we have 30,244 household-year observations between 2004 and 2014.[8] Tradable consumption is defined as expenditures on clothing, food at home, prescriptions, home furnishings, the purchase and lease of cars and trucks, 22 percent of entertainment and vacation, and 21 percent of housing and vehicle repairs. Total consumption is defined as expenditures on child care, clothing, education, food, health care, housing (except expenditures on mortgage, property taxes, and homeowner's and renter's insurance), transportation, vacation and entertainment, and in the case of homeowners, we add owner's equivalent rent.[9]

[8] We start our analysis in 2004 because that is when the PSID expanded its collection of expenditure data.

[9] We use information on the price-to-rent ratios at the state level and the self-reported market value of the household's main home to impute the owner's equivalent rent.

Disposable labor income is constructed in the same manner as described in the previous paragraph. For wealth, we use a broad measure of net worth, which includes stocks, real estate, noncorporate business assets, bonds, checking and savings accounts, and vehicles, minus debts. In both data sets, we restrict the sample to households whose heads are between the ages of 25 and 64, and those with positive amounts of disposable labor income and wealth.[10]

The data sets we use are complementary. Compared to the PSID, the CEX has the advantage of providing more disaggregated expenditures and self-reported owner's equivalent rent values. However, the CEX provides a narrower measure of wealth. Thus, we use both data sources to document our findings. Compared to widely used scanner data, which has much more detailed expenditure information but only reports a small fraction of total household expenditures and has limited information on income and wealth, the PSID and CEX provide information on most household expenditures and detailed information on income, wealth, and other household characteristics.

2.2 Tradable expenditure, income, and wealth

Figure 1 plots the relation between tradable expenditure shares and disposable labor income in the (a) PSID and the (b) CEX. While the measured tradable expenditure shares are higher in the CEX than in the PSID, the pattern is the same across both data sets. Households with lower disposable labor income consume a higher share of tradable goods. The lowest and highest income deciles average tradable expenditure shares of 37 and 31 percent, respectively, across the two data sets.

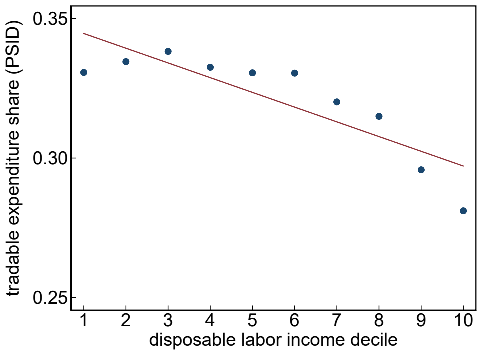
Figure 2 shows that the pattern is even stronger for wealth. The lowest and highest wealth deciles average tradable expenditure shares of 39 and 30 percent, respectively, across the two data sets.

To document the relation in a more systematic way, we regress tradable expenditure shares on the natural logarithm of wealth and disposable labor income, along with fixed effects for time and household characteristics. Table 1 summarizes our findings using the PSID and the CEX data. The negative relationship between tradable share and disposable

[10]See Appendix A for additional details.

Figure 1: Tradable expenditure shares and disposable labor income

(a) PSID



(b) CEX

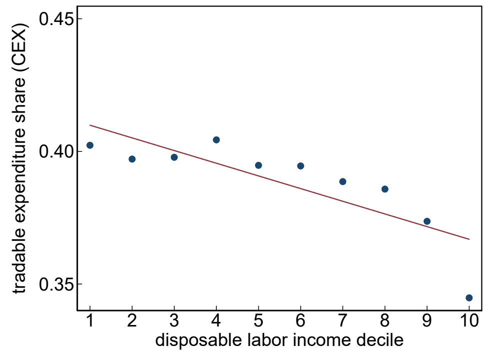
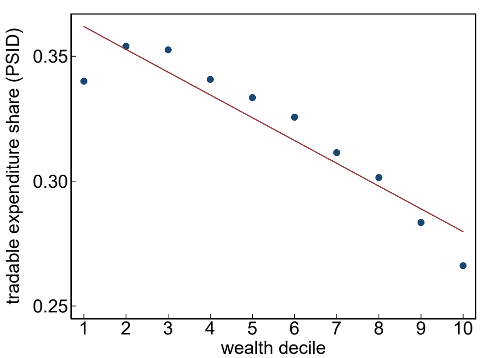
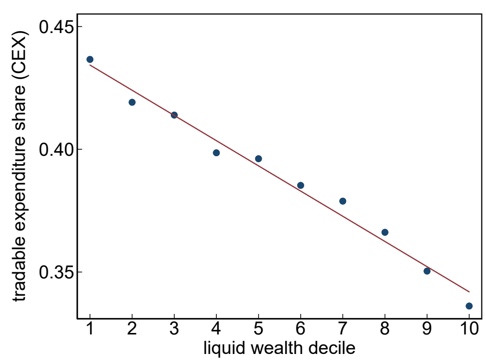


Figure 2: Tradable expenditure shares and wealth

(a) PSID



(b) CEX



labor income and wealth is robust to controlling for age and education of the household head, household size, and homeownership, with all the wealth coefficients being significant at the 1 percent level.

Table 1: Tradable shares, wealth, and income

	Tradable expenditure share (percent)					
	(1)	(2)	(3)	(4)	(5)	(6)
	PSID	PSID	PSID	CEX	CEX	CEX
Wealth	–1.07***	–1.03***	–0.64***	–1.09***	–1.12***	–0.37***
	(0.03)	(0.04)	(0.05)	(0.03)	(0.04)	(0.04)
Income		–0.20**	–0.46***		–0.24*	–1.17***
		(0.09)	(0.10)		(0.13)	(0.14)
College			–2.77***			–3.31***
			(0.15)			(0.19)
Homeowner			–1.31***			–6.06***
			(0.19)			(0.21)
Other household controls	no	no	yes	no	no	yes
Observations	30244	30244	30228	23484	23484	23484
Adjusted R^2	0.036	0.036	0.066	0.076	0.076	0.167

Standard errors in parentheses. All regressions include year fixed effects.
Other household controls include fixed effects for age and household size.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The coefficients are sizable. For example, using the coefficients in columns (3) and (6), one standard deviation increases in log wealth are associated with declines in the tradable expenditure share of 1.3 and 1.0 percentage points in the PSID and CEX, respectively. Similarly, one standard deviation increases in log income are associated with declines in the tradable expenditure share of 0.4 and 0.9 percentage points in the PSID and CEX, respectively.

We show in Appendix A.3 that our results are robust to excluding housing costs (rent, owner's equivalent rent, mortgage, property taxes, renter's and homeowner's insurance), to treating all expenditures on entertainment, vacation, and housing and vehicle repairs as nontradable, to using total labor income, and to using an alternative tradability definition which includes indirect imports.

Having established a negative empirical relationship between tradable expenditure share and income or wealth, we next construct a dynamic general equilibrium model with incomplete markets and nonhomothetic preferences to measure the quantitative importance of this relationship for welfare.

3 Model

We consider a two-country model with balanced trade without labor or capital flows. There are a continuum of tradable goods indexed by ω and a single nontradable numeraire. For convenience we drop time subscripts.

3.1 Households

Each country is populated by a mass L_i of households that consume a nontradable good, c_N, and a tradable good, c_T. We assume a separable period utility function

$$u\left(c_T, c_N\right) = \frac{\left[c_T^{\gamma}\left(c_N + \bar{c}\right)^{1-\gamma}\right]^{1-\sigma}}{1-\sigma}.$$

When $\bar{c} > 0$, the utility function represents Stone-Geary nonhomothetic preferences. Labor is perfectly substitutable across sectors, so there is a single efficiency wage rate, w_i. Households face uninsurable idiosyncratic productivity risk. Each period, a household draws a realization of labor productivity ε from a finite set $\mathcal{E}$ and earns a wage $w_i\varepsilon$. We assume that ε follows a Markov process with transition matrix $\Gamma\left(\varepsilon', \varepsilon\right)$. There are no state-contingent claims, so households can only self-insure through buying and accumulating capital, k. The law of motion for capital follows $k' = k(1-\delta) + x$ where δ is the depreciation rate of capital and x is investment, which is purchased at price P_{iX}. A unit of capital has a net return of $\tilde{r} \equiv r_i - \delta P_{iX}$ in the next period.

3.2 Nontradables producer

A perfectly competitive representative firm in country i produces nontradable output Y_{iN} using labor and capital according to

$$Y_{iN} = z_{iN} L_{iN}^{\alpha_N} K_{iN}^{1-\alpha_N} \tag{1}$$

where z_{iN} is a fixed level of productivity. It solves a static profit-maximization problem

$$\max_{L_{iN}, K_{iN}} P_{iN} Y_{iN} - w_i L_{iN} - r_i K_{iN} \tag{2}$$
$$\text{s.t. (1).}$$

3.3 Final tradables producer

A representative final tradables producer in country i bundles the varieties of tradable goods produced in country $o = 1, 2$, $q_{oi}(\omega)$, into a single homogeneous consumption good, Y_{iT}, according to

$$Y_{iT} = \left(\int_0^1 \left[\sum_{o=1,2} q_{oi}(\omega) \right]^{\rho} d\omega \right)^{\frac{1}{\rho}} \tag{3}$$

and sells it to consumers at price, P_{iT}. The varieties in the bundle $q_{oi}(\omega)$ are purchased from intermediate tradable producers in country o at price $p_o(\omega)$. Given $\{p_o(\omega)\}$ for $o = 1, 2$ and $\omega \in [0, 1]$ and P_{iT}, the producer in country i solves

$$\max_{\{q_{oi}(\omega)\}_{j=1,2}} P_{iT} Y_{iT} - \int_0^1 \left[\sum_{o=1,2} \tau_{oi} p_o(\omega) q_{oi}(\omega) \right] d\omega \tag{4}$$
$$\text{s.t. (3)}$$

where $\tau_{oi} - 1$ is an iceberg trade cost and satisfies $\tau_{oi} = 1$ for $i = o$ and $\tau_{oi} \geq 1$ for $i \neq o$. Note that the producer in country i will purchase a variety ω from the lowest cost producer.[11]

[11] Without loss of generality, we assume that the producer sources domestically in the case where costs are equal.

Then, the producer's optimality conditions are given by

$$q_{oi}(\omega) \leq \left(\frac{\tau_{oi} p_o(\omega)}{P_{iT}}\right)^{-\theta} Y_{iT}, \tag{5}$$

which holds with equality if $q_{oi}(\omega) > 0$. Furthermore, the tradables price is given by

$$P_{iT} = \left[\int_0^1 \min_o \left\{\tau_{oi} p_o(\omega)\right\}^{1-\theta} d\omega\right]^{\frac{1}{1-\theta}} \tag{6}$$

where $\theta = \frac{1}{1-\rho}$ is the elasticity of substitution across varieties.

3.4 Intermediate tradables producer

A representative intermediate tradables firm in country i produces a single variety, ω, of tradable good and hires labor and capital to produce according to the production function

$$y_i(\omega) = z_i(\omega) l_i(\omega)^{\alpha_T} k_i(\omega)^{1-\alpha_T}. \tag{7}$$

Taking prices $p_i(\omega)$ as given, the producer solves

$$\max_{l_i(\omega), k_i(\omega)} p_i(\omega) y_i(\omega) - w_i l_i(\omega) - r_i k_i(\omega) \tag{8}$$
$$\text{s.t. } (7).$$

The intermediate firm's optimality conditions are given by

$$w_i = p_i(\omega) z_i(\omega) \alpha_T \left[\frac{k_i(\omega)}{l_i(\omega)}\right]^{1-\alpha_T}, \tag{9}$$

$$r_i = p_i(\omega) z_i(\omega)(1-\alpha_T) \left[\frac{k_i(\omega)}{l_i(\omega)}\right]^{-\alpha_T}. \tag{10}$$

We assume that the productivities for variety ω in each country are given by

$$z_1(\omega) = e^{\eta\omega}, \tag{11}$$

$$z_2(\omega) = e^{\eta(1-\omega)} \tag{12}$$

so that country $i = 1$ (2) has a higher productivity for high (low) ω varieties.

3.5 Capital producer

The representative capital producer in country i produces investment goods by combining tradable and nontradable goods according to

$$X_i = z_{iX} I_{iT}^{\kappa} I_{iN}^{1-\kappa}. \tag{13}$$

Taking prices P_{iT}, P_{iN}, and P_{iX} as given, the producer solves

$$\max_{I_T, I_N} P_{iX} X_i - P_{iT} I_{iT} - P_{iN} I_{iN} \tag{14}$$

$$\text{s.t. } (13).$$

The capital producer's optimality conditions are given by

$$P_{iT} = \kappa P_{iX} z_{iX} I_{iT}^{\kappa-1} I_{iN}^{1-\kappa}, \tag{15}$$

$$P_{iN} = (1-\kappa) P_{iX} z_{iX} I_{iT}^{\kappa} I_{iN}^{-\kappa}. \tag{16}$$

3.6 Recursive formulation

The problem of a household in country i can be stated as

$$V_i(k, \varepsilon) = \max_{c_T, c_N, k'} u(c_T, c_N) + \beta E_{\varepsilon'|\varepsilon} V_i(k', \varepsilon') \tag{17}$$

$$\text{s.t. } P_{iT} c_T + P_{iN} c_N + P_{iX}(k' - k) \leq w\varepsilon + \tilde{r}k$$

$$k' \geq 0$$

Solving this yields decision rules $g_{iT}(k,\varepsilon)$, $g_{iN}(k,\varepsilon)$, and $g_{ik}(k,\varepsilon)$ for tradable consumption, nontradable consumption, and capital, respectively. Define the state space over wealth and labor productivity as $S = K \times E$ and let a σ-algebra over S be defined by the Borel sets, $\mathcal{B}$, on S.

Definition. A *steady state recursive equilibrium* is, for $i = 1, 2$, a collection of functions $\{V_i, g_{iT}, g_{iN}, g_{ik}\}$, prices $\left\{r_i, w_i, P_{iT}, P_{iN}, P_{iX}, \{p_i(\omega)\}_{\omega\in[0,1]}\right\}$, nontradable producer plans $\{Y_{iN}, L_{iN}, K_{iN}\}$, final tradable producer plans $\left\{Y_{iT}, \{q_{oi}(\omega)\}_{\omega\in[0,1],o=1,2}\right\}$, intermediate tradable producer plans $\{y_i(\omega), l_i(\omega), k_i(\omega)\}_{\omega\in[0,1]}$, capital producer plans $\{X_i, I_{iT}, I_{iN}\}$, and invariant distributions $\{\mu_i^*\}$ such that

1. Given $\{r_i, w_i, P_{iT}, P_{iN}, P_{iX}\}$, $\{V_i, g_{iT}, g_{iN}, g_{ik}\}$ satisfy the household problem in (17).
2. Given $\{r_i, w_i, P_{iN}\}$, $\{Y_{iN}, L_{iN}, K_{iN}\}$ solve the problem in (2).
3. Given $\{P_{iT}, \{p_1(\omega), p_2(\omega)\}_\omega\}$, $\{Y_{iT}, \{q_{i1}(\omega), q_{i2}(\omega)\}_\omega\}$ solve the problem in (4).
4. Given $\{r_i, w_i, p_i(\omega)\}$, $\{y_i(\omega), l_i(\omega), k_i(\omega)\}$ solve the problem in (8) for $\omega \in [0,1]$.
5. Given $\{P_{iT}, P_{iN}, P_{iX}\}$, $\{X_i, I_{iT}, I_{iN}\}$ solve the problem in (14).
6. Markets clear:
   (a) $Y_{iN} = \int g_{iN}(k,\varepsilon)\, d\mu_i^*(k,\varepsilon) + I_{iN}$,
   (b) $Y_{iT} = \int g_{iT}(k,\varepsilon)\, d\mu_i^*(k,\varepsilon) + I_{iT}$,
   (c) $X_i = \delta \int g_{ik}(k,\varepsilon)\, d\mu_i^*(k,\varepsilon)$,
   (d) $y_i(\omega) = \tau_{i1} q_{i1}(\omega) + \tau_{i2} q_{i2}(\omega)$ for $\omega \in [0,1]$,
   (e) $L_{iN} + \int_0^1 l_i(\omega)\, d\omega = L_i \int \varepsilon d\mu_i^*(k,\varepsilon)$.
7. Trade is balanced: $\int_0^1 p_1(\omega)\, q_{12}(\omega)\, d\omega = \int_0^1 p_2(\omega)\, q_{21}(\omega)\, d\omega$.
8. For any subset $(\mathcal{K}, \mathcal{E}) \in \mathcal{B}$, μ_i^* satisfies

$$\mu_i^*(\mathcal{K}, \mathcal{E}) = \int_S \sum_{\varepsilon' \in \mathcal{E}} 1_{\{g_{ik}(k,\varepsilon)\in\mathcal{K}\}} \Gamma(\varepsilon', \varepsilon)\, d\mu_i^*(k,\varepsilon).$$

3.7 Characterization of equilibrium

For simplicity, we assume that the two countries are identical except for the intermediate tradable productivities, which are as specified in equations (11)–(12), so that $w = w_1 = w_2$, $r = r_1 = r_2$, $\tau = \tau_{12} = \tau_{21}$, et cetera. In what follows, we will omit the country notation unless necessary. We normalize the price of nontradables, by setting $P_N = 1$.

By substituting equation (9) into (10), we obtain the price of variety ω produced in country i,

$$p_i(\omega) = \frac{1}{z_i(\omega)} \left(\frac{w}{\alpha_T}\right)^{\alpha_T} \left(\frac{r}{1-\alpha_T}\right)^{1-\alpha_T}. \tag{18}$$

In equilibrium, there are two thresholds that determine the production of the intermediate tradable goods. For $\omega > \bar{\omega}(\tau)$, production takes place only in country $i = 1$, where

$$\bar{\omega}(\tau) = \min\left\{1, \frac{\eta + \log \tau}{2\eta}\right\}, \tag{19}$$

which can be obtained from the condition $\tau p_2(\bar{\omega}(\tau)) = p_1 \bar{\omega}(\tau)$. By symmetry, for $\omega < 1 - \bar{\omega}(\tau)$, production takes place only in country $i = 2$. Both countries produce the varieties $\omega \in [1 - \bar{\omega}(\tau), \bar{\omega}(\tau)]$. Figure 3 illustrates the pattern of production, trade, and specialization. Note that when $\tau = 1$, we obtain $\bar{\omega}(\tau) = 1/2$, which corresponds to free trade and full specialization, and when $\tau > e^\eta$, we obtain $\bar{\omega}(\tau) = 1$, which corresponds to autarky.

Substituting the price in (18) into the tradable price aggregator in (6), we obtain

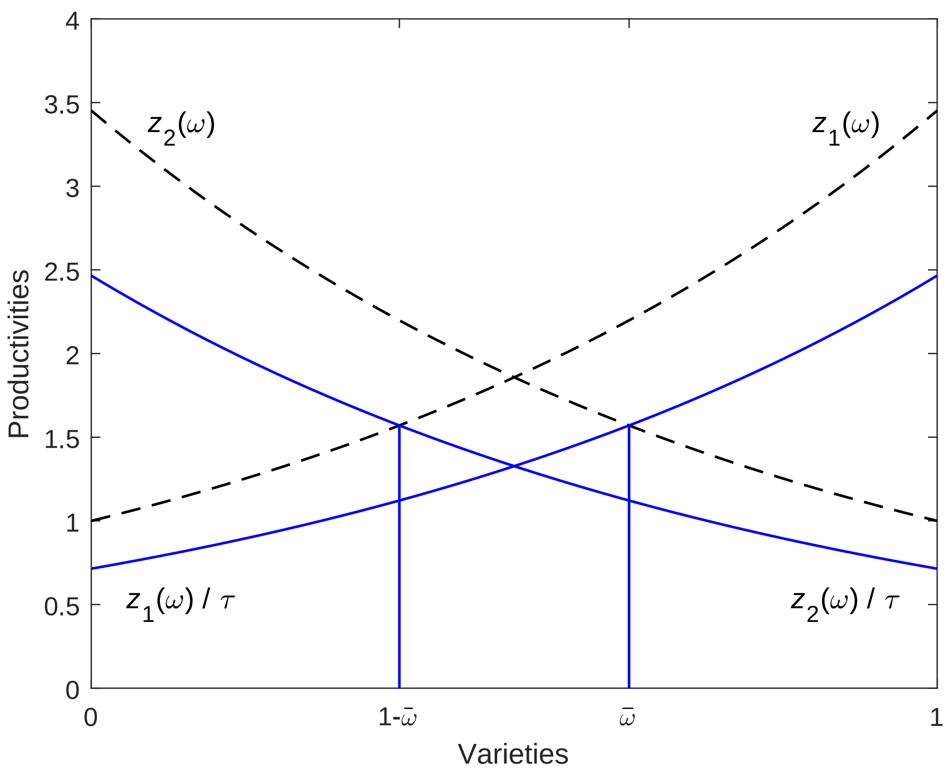
$$P_T = \frac{1}{\tilde{z}(\tau)} \left(\frac{w}{\alpha_T}\right)^{\alpha_T} \left(\frac{r}{1-\alpha_T}\right)^{1-\alpha_T} \tag{20}$$

where $\tilde{z}(\tau)$ is a measure of average productivity:

$$\tilde{z}(\tau) = \left[\tau^{1-\theta} \int_0^{1-\bar{\omega}(\tau)} z_2(\omega)^{\theta-1} \, d\omega + \int_{1-\bar{\omega}(\tau)}^{1} z_1(\omega)^{\theta-1} \, d\omega\right]^{\frac{1}{\theta-1}}. \tag{21}$$

Note that $d\tilde{z}(\tau)/d\tau < 0$, i.e., lower trade costs result in higher average productivity. Com-

Figure 3: Pattern of production, trade, and specialization



bining the capital producer's optimality conditions in equations (15) and (16), we obtain

$$P_X = \frac{1}{z_X}\left(\frac{P_T}{\kappa}\right)^{\kappa}\left(\frac{1}{1-\kappa}\right)^{1-\kappa}. \tag{22}$$

In the special case that $\alpha_N = \alpha_T$, the tradable price further simplifies to

$$P_T = \frac{z_N}{\tilde{z}(\tau)}. \tag{23}$$

In this case, it is straightforward to show that

$$\frac{d\log\left(P_T\right)}{d\tau} = -\frac{d\log\left(\tilde{z}(\tau)\right)}{d\tau} > 0 \tag{24}$$

and

$$\frac{d\log\left(P_X\right)}{d\tau} = -\kappa\frac{d\log\left(\tilde{z}(\tau)\right)}{d\tau} > 0. \tag{25}$$

That is, lower trade costs decrease the price of tradables by increasing average productivity in the tradable sector and, to a lesser extent, decrease the price of investment. We will quantitatively analyze the effects of a change in trade costs in the next section.

4 Quantitative Analysis

4.1 Calibration

We choose parameters so that the model's steady state equilibrium matches several features of the U.S. economy. We summarize the parameters in Table 2.

We set the household's discount factor β, so that the model matches the net-worth-to-GDP ratio in the U.S., 4.8 (2014, *U.S. Financial Accounts*). We choose the tradable share parameter, γ, and the nonhomothetic preference parameter, $\bar{c}$, so that the model matches the average tradable expenditure shares in the U.S. of 36 percent and that of the top 10 percent of the wealth distribution, 30 percent (2004–2014, PSID and CEX).

We set the labor elasticities in tradables and nontradables production to $\alpha_T = \alpha_N = 0.64$

to match the aggregate labor share.[12] The parameter that governs the curvature of the productivity distribution, η, is set so that, conditional on exporting, the employment share of the top 17 percent of exporters is 32.1 percent. For the empirical counterpart, we compute the employment share of the top 17 percent of large U.S. manufacturing establishments (at least 100 employees), which is 32.1 percent (2014, U.S. Census, *Business Dynamics Statistics*).[13] The elasticity of substitution between tradable varieties θ is calibrated so that the import elasticity with respect to trade costs is 4.0, which is within the range of estimates by Simonovska and Waugh (2014). We set the tradable share in capital production, κ, to match the tradable share of capital production inputs calculated from the U.S. input-output table, 59 percent (2014, *Bureau of Economic Analysis*). We set the iceberg trade cost $\tau_T - 1$ to match the U.S. import share of GDP, 17 percent (2014, *World Bank*).

The labor productivity shocks ε are assumed to follow an order-one autoregressive process as follows:

$$\log \varepsilon_t = \rho_\varepsilon \log \varepsilon_{t-1} + \nu_t, \nu_t \sim N\left(0, \sigma_\varepsilon^2\right) \tag{26}$$

We estimate this process using disposable labor income from the PSID to find persistence $\rho_\varepsilon = 0.93$ and standard deviation $\sigma_\nu = 0.24$.[14] This process is approximated with a five-state Markov process using the Rouwenhurst procedure described in Kopecky and Suen (2010). We set the household's risk aversion, σ, to be 2, a standard value in the literature. Finally, we normalize the productivities in the nontradable and capital sectors, $z_N = z_X = 1$.

4.2 Quantitative exercise: Reduction in the cost of trade

In this subsection, we use our calibrated model to analyze the distributional impacts from a trade. In particular, we generate a high-cost steady state economy by increasing trade costs, keeping all other parameters fixed, to generate an import share of 13 percent. The economy begins in the high-cost steady state. At the beginning of time $t = 1$, a shock hits

[12] Kehoe et al. (2018) use sectoral data to compute capital shares of 0.33 and 0.35 for goods and services, respectively.

[13] Ideally, we would target the size distribution of exporting establishments. Without access to those data, we are using the set of large manufacturing establishments as a proxy for the set of exporting establishments.

[14] The sample selection and estimation procedures closely follow Krueger et al. (2016) and Hur (2018). See Appendix A.3 for details. Notice that our estimates are similar to Floden and Lindé (2001), who estimate a similar process for wages.

Table 2: Calibration

Parameters	Values	Targets / Source
Discount factor β	0.97	Wealth-to-GDP: 4.8
Risk aversion σ	2	Standard value
Tradable share γ	0.26	Tradable expenditure share: 36 percent
nonhomotheticity $\bar{c}$	0.19	Tradable expenditure share of wealthiest decile: 30 percent
Factor elasticities α_T, α_N	0.64	Labor income share
Factor elasticity κ	0.59	Tradable input shares in capital production
Elasticity of substitution θ	5.72	Trade elasticity: 4.0
Productivity distribution η	1.29	Employment share of top 17 percent of large manufacturing establishments: 32 percent
Iceberg trade cost $\tau - 1$	0.04	Import share: 17 percent
Persistence ρ_ε	0.93	Authors' estimates
Standard deviation σ_ν	0.24	Authors' estimates

that reduces τ for both countries, and, over time, the economy transitions to its new low-cost steady state.[15]

Because the wealth distribution evolves over time, prices and household decisions are also time-dependent. For clarity, we introduce time subscripts to make explicit that the value function and decision rules depend upon $\mu_t(k, \varepsilon)$.

The household problem can be stated recursively as

$$
\begin{aligned}
V_t(k,\varepsilon) = \max_{c_T, c_N, k'} \; & u(c_T, c_N) + \beta E_{\varepsilon_{t+1}|\varepsilon} V_{t+1}(k', \varepsilon_{t+1}) \\
\text{s.t.} \quad & P_{Tt} c_T + c_N + P_{Xt}(k' - k) \leq \tilde{w}_t \bar{h} \varepsilon + \tilde{r}_t k, \\
& k' \geq 0
\end{aligned}
\tag{27}
$$

Solving this yields time-dependent decision rules $g_{Tt}(k,\varepsilon)$, $g_{Nt}(k,\varepsilon)$, and $g_{kt}(k,\varepsilon)$ for tradables consumption, nontradables consumption, and saving, respectively.

To solve the transition, we start with the stationary wealth distribution of the high-cost steady state, μ_0^*, at $t = 0$ and then solve for a sequence of value functions $\{V_t\}_{t=1}^{\infty}$, decision

[15] This experiment roughly corresponds to the "China trade shock."

rules $\{g_{Tt}, g_{Nt}, g_{kt}\}_{t=1}^{\infty}$, wealth distributions $\{\mu_t\}_{t=1}^{\infty}$, and prices $\{r_t, w_t, P_{Tt}, P_{Xt}, \{p(\omega)\}_{\omega}\}_{t=1}^{\infty}$, such that given prices, households and firms make optimal decisions, markets clear, and distributions are consistent with household savings decisions.

4.2.1 Effect on aggregates

Increasing the import share from 13 percent to 17 percent requires a decrease in τ from 1.12 to 1.04. The final tradables producer responds to the lower cost of foreign varieties by shifting the composition of its inputs toward imports ($\bar{\omega}$ decreases). Average productivity, $\tilde{z}(\tau)$, jumps up 2.8 percent. As shown in Figure 4, this rise in $\tilde{z}(\tau)$ induces three immediate effects: the price of tradables falls by 2.7 percent, the price of investment falls by 1.6 percent, and the net return on capital increases by 5 basis points. The first effect follows directly from equation (23), while the second effect is a consequence of the first, since the final tradable good is an input into capital production (equation (22)). The jump in the net return is entirely a result of a reduction in depreciation cost, δP_X, due to a lower investment price.

After the initial responses, the economy starts on a transition path characterized by capital deepening, as the lower investment price and higher net return encourage more saving. Over time, as capital becomes more abundant, the net return on capital declines and the wage rises.

A reduction in trade costs leads to higher real economic activity in the long run. Figure 5 plots the transition path of the main aggregate variables. Real GDP rises by 2.1 percent, while real household consumption is 1.9 percent greater in the low-cost steady state. Both long-run investment and the long-run capital stock are 2.7 percent greater.

Across production sectors, the allocation of factors shifts from nontradable to tradable. Figure 6 plots the transition path of K_T, K_N,L_T, and L_N to the low-cost steady state. Both capital and labor immediately exit the nontradable sector for the tradable sector. After the initial reallocation, the composition of factors slowly begins shifting back again. Note that in all periods the capital-to-effective labor ratio is the same in both sectors. This is because they share common factor prices and factor intensities.

Figure 4: Prices

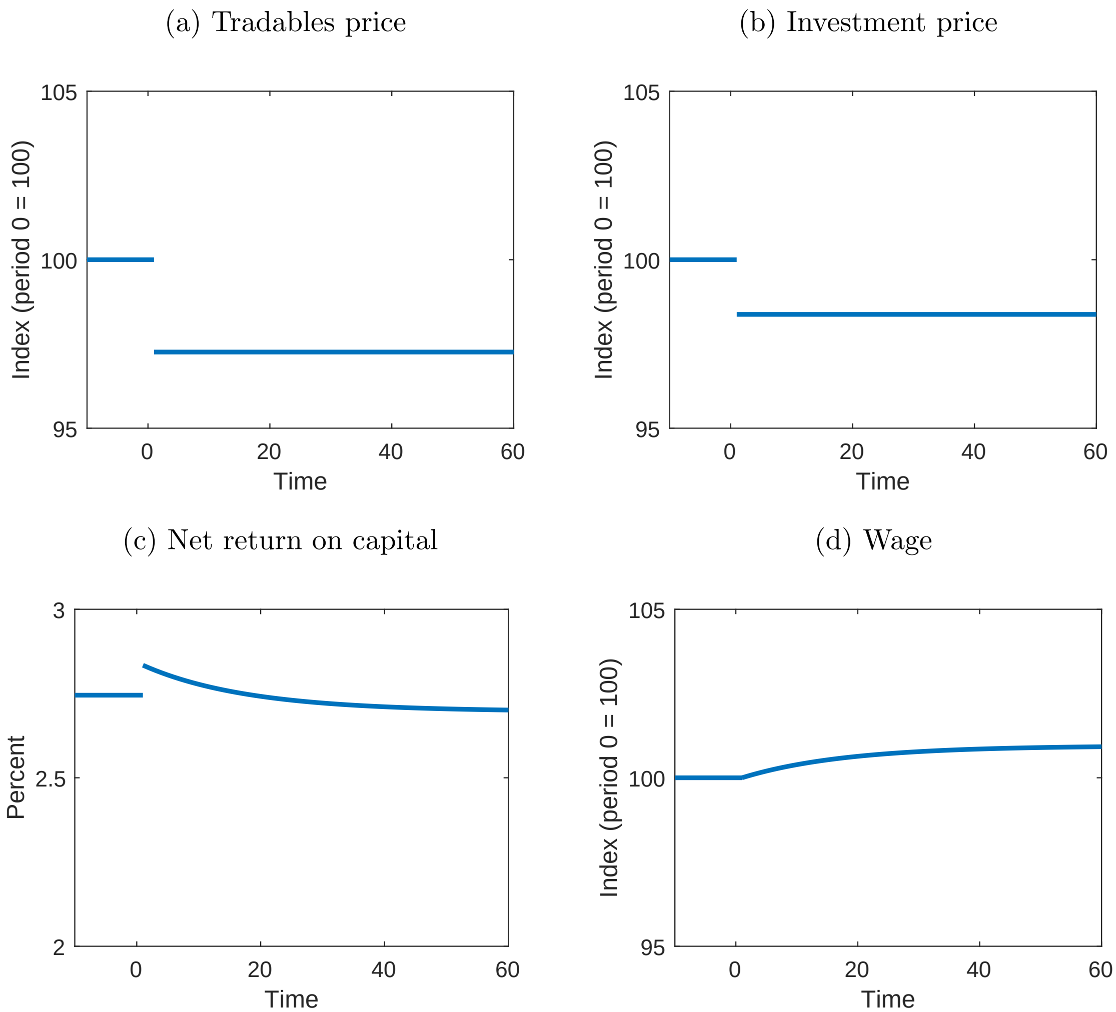
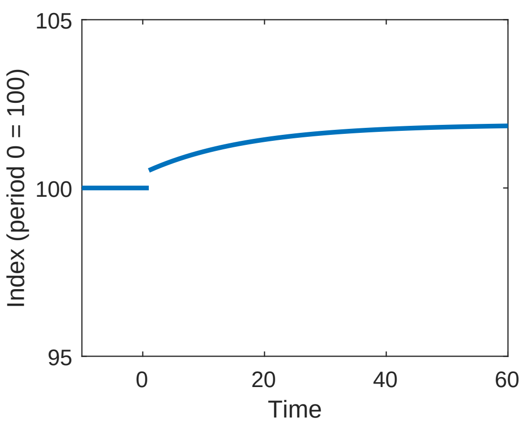
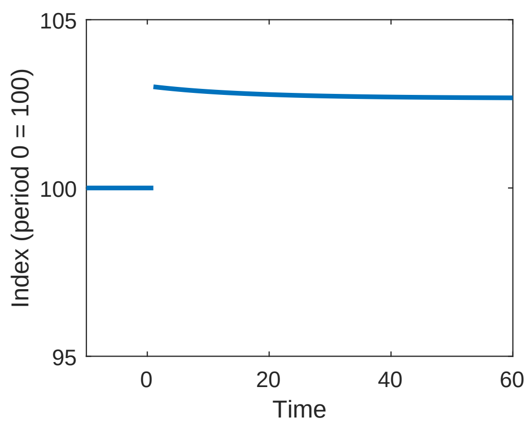


Figure 5: Quantities

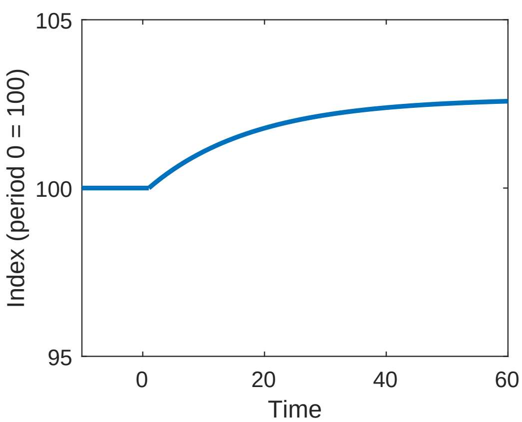
(a) Consumption



(b) Investment



(c) Capital



(d) GDP

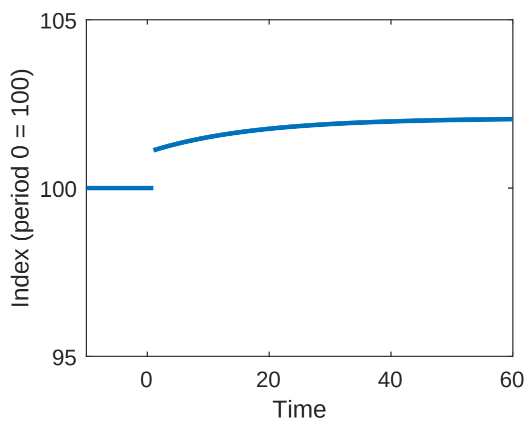
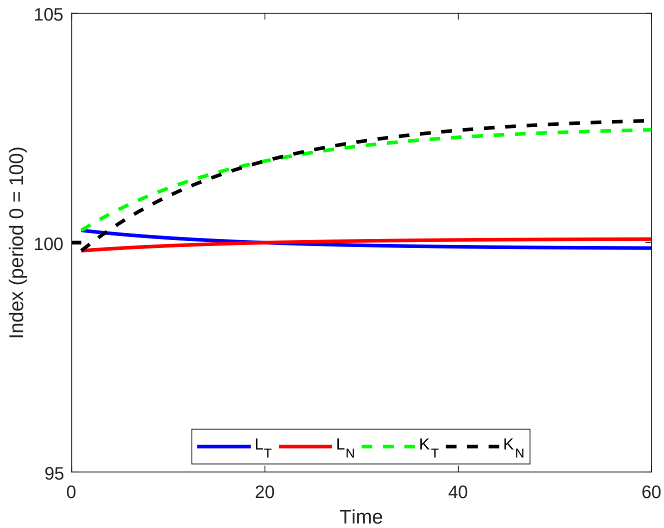


Figure 6: Sectoral reallocation



4.2.2 Welfare costs

The dynamics of prices resulting from a reduction in trade costs lead to differential effects on household welfare across wealth and income. We calculate the distribution of welfare using consumption equivalence. That is, we compute, for each household, by what common percentage, Δ, initial steady state tradables and nontradables consumption would have to be permanently increased in order to make a household indifferent to the reduction in trade costs. Positive values of Δ indicate that a household benefits from the lowering costs. Formally, given the household value functions at the beginning of the transition, $V_1(k, \varepsilon)$, and the initial steady state decision rules, g_k^{ss}, g_T^{ss}, and g_N^{ss}, we solve for $\Delta(k, \varepsilon)$, such that

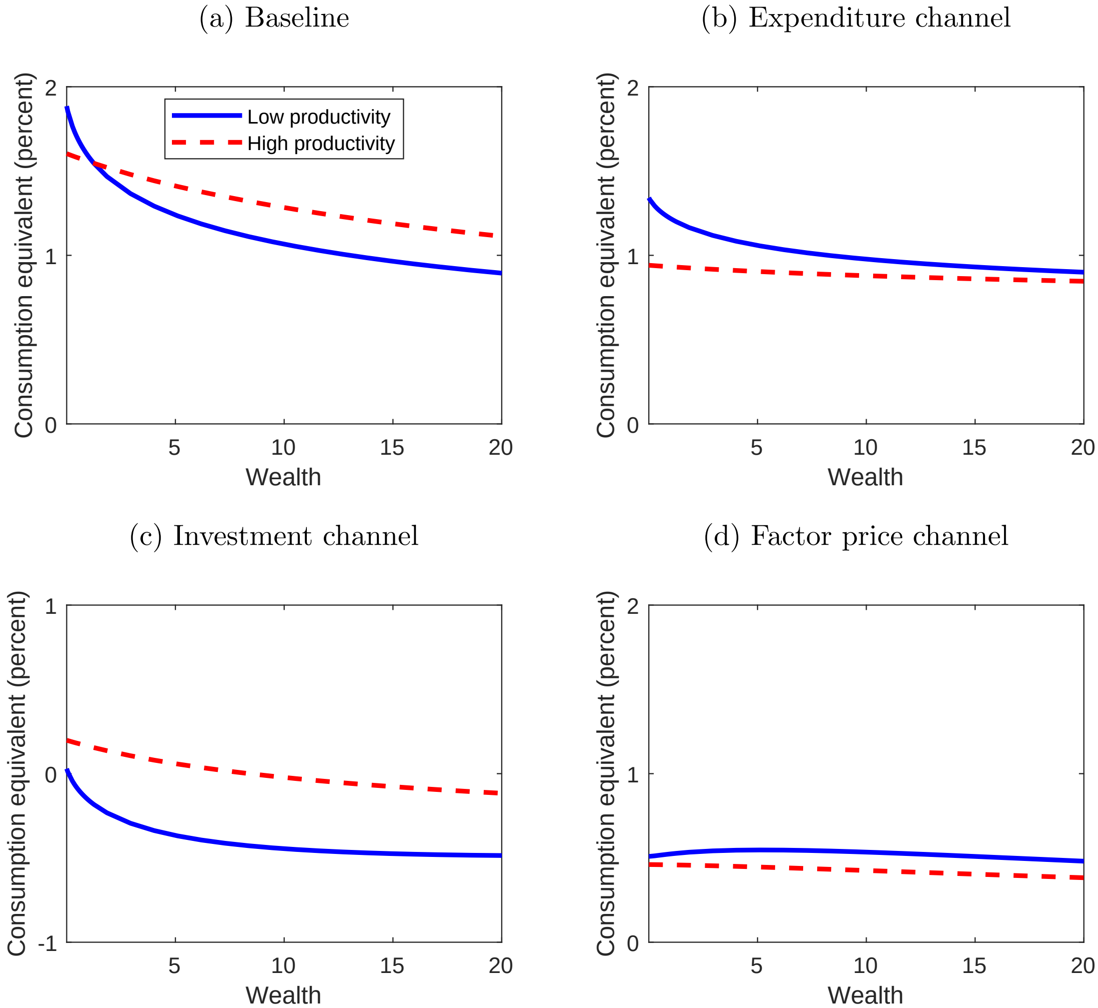
$$V_\Delta(k, \varepsilon) = V_1(k, \varepsilon)$$

where

$$V_\Delta(k, \varepsilon) = u\left((1 + \Delta) * g_T^{ss}, (1 + \Delta) * g_N^{ss}\right) + \beta E_{\varepsilon'|\varepsilon} V_\Delta\left(g_k^{ss}, \varepsilon'\right).$$

Figure 7(a) plots Δ across the wealth distribution at the moment the policy change is announced for low-productivity and high-productivity households.

Figure 7: Welfare change



First, notice that all households benefit from the reduction in trade costs. The average welfare gain across all households is 1.43 percent. Second, the welfare gains are not equally distributed, but rather decrease with wealth. A low-income household with no wealth would require a permanent increase in initial steady state consumption of 1.89 percent to forgo the low trade cost transition, while the average welfare gain for the richest decile of households is only 1.06 percent.

We decompose the total welfare gains into the interaction of three channels: the *expenditure* channel, the *investment* channel, and the *factor price* channel. The expenditure channel captures the change in welfare arising from changes in a household's consumption bundle resulting from the reduction in the relative price of the final tradable good. This channel has the strongest influence on poor households because of their larger expenditure share on tradable goods.

Since tradable goods are also an input of capital production, a lower tradable price leads to an increase in the price of investment that alters the cost of saving. This is the investment channel, and it has opposite welfare effects depending upon whether a household is a buyer or a seller of capital. High-productivity, low-wealth households benefit most. These households have a strong desire to accumulate assets for precautionary saving, and the reduction in the investment price comes at a particularly apropos time. Meanwhile, low-productivity, high-wealth households that wish to smooth consumption by selling assets are made worse off.

Finally, the lower investment price leads to capital deepening and lower depreciation costs. This leads to a temporary rise in the net return on capital and a permanent rise in wages. We assign the welfare effects from these changes to the factor price channel. The factor price channel affects households heterogeneously depending upon the composition of their income between labor and capital. A low-wealth household—whose income is almost entirely from labor—benefits more than a wealthy household does when wages rise, and it benefits less when interest rates rise.

In order to quantify the importance of each of these channels, we conduct a sequence of partial equilibrium exercises. We introduce a measure-zero collection of "ghost" households, which face prices that are different from the equilibrium prices faced by regular households.

Ghosts still optimize in response to the prices they face, but because they are zero measure, their cumulative activity has no effect on the equilibrium. We compare three ghost types. The first ghost type only experiences the change in the equilibrium price of tradables; the second type only faces the equilibrium path of investment prices; and for the final ghost type, only the wage and net return on capital follow their equilibrium paths.

Figure 7(b) plots the consumption equivalents across wealth and income for the first ghost type. In this case, only the tradable price changes. It is evident that the expenditure channel accounts for most of the welfare gain, and it is particularly important for low-wage, low-wealth households. On average, the expenditure channel, which contributes positively to welfare for all households, increases welfare by 1.03 percent.

Figure 7(c) plots the distribution of welfare changes from the investment channel. Low-productivity households are typically sellers of capital and are harmed by the fall in the price of investment. Notice, though, that the welfare costs to low-productivity households with very little wealth are small, with households with no wealth even receiving a very small welfare *gain*. This results from the combination of two factors: first, these households have very few assets to sell. Second, these low-productivity households still face a positive probability of drawing a higher wage in the future, at which point they would certainly become buyers of capital again. In expectation, this results in a small welfare gain. In contrast, high-productivity, low-wealth households are buyers of capital and, as a consequence, gain from a decline in P_X. On average, the investment channel reduces welfare by 0.10 percentage points, but wealthy low-wage households lose about 0.48 percentage points and poor high-wage households gain 0.20 percentage points.

Finally, the welfare costs for the third ghost type are plotted in Figure 7(d). In this case, only $\tilde{r}$ and $\tilde{w}$ change. The factor price channel contributes positively to total welfare for all households. The wage increases over the transition, disproportionately benefiting the wealth-poor, since labor income constitutes a larger portion of their total income. Although in the long run the net return on capital is lower in the low-cost steady state, the short- and medium-run dynamics of $\tilde{r}$ more than make up for it. On average, the factor price channel contributes 0.50 percentage points to the total welfare change.

We find that the welfare change of a regular household in state (k, ε) is well approximated by the sum of the welfare changes of each ghost type at (k, ε). Thus, we can use these ghost cases as a measure of the approximate contribution to the total welfare loss coming from the three channels. In Table 3, we report the average welfare change for each ghost type for the lowest and highest productivity levels in the bottom and top deciles of the wealth distribution. Among any group, the most important factor for welfare changes is the increase in the price of tradables (expenditure channel).

Table 3: Decomposition of welfare changes

Average	Low wealth		High wealth		Average
	Low prod.	High prod.	Low prod.	High prod.	
Expenditure	1.34	0.94	0.92	0.85	1.03
Investment	0.03	0.20	−0.48	−0.10	−0.10
Factor price	0.51	0.46	0.50	0.39	0.50
All	1.89	1.60	0.94	1.13	**1.43**

Units: percent.

5 Conclusion

We have documented that the share of household consumption expenditure on tradable goods is a decreasing function of household income and wealth. This implies that low-income and low-wealth households could benefit more from increased trade, which lowers the price of tradable consumption goods. We calibrate a two-country dynamic stochastic general equilibrium model with incomplete markets and nonhomothetic preferences and use it to measure the welfare consequences of a reduction in trade costs that leads to an increase in import share on par with that observed in the data from 2001 to 2014. All households gain from increased trade, but poor households receive the largest welfare gains. While the primary contributor to the rise in welfare is a reduction in the price of tradable consumption, changes in wages and net returns to capital contribute roughly one-third of the total welfare gain. Additionally, a fall in the price of investment is an important factor for poor households with high wages, as it makes precautionary saving less expensive, but significantly harms households trying to smooth consumption by making current capital less valuable.

We see this model as an interesting laboratory to explore the consequences of tariff policy. We leave this potential extension and the study of optimal trade and fiscal policies in a richer framework for future research.

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A Data

A.1 Consumer Expenditure Survey (CEX)

From the Consumer Expenditures Survey's interview microdata, we append expenditure (mbti) files from 2004 to 2014 into one data set. This data set contains one entry for each expenditure by a consumer unit (CU) in an interview period. We similarly append family characteristics (fmli) files from 2004 to 2014 into one data set, which contains one entry for each CU. We keep wealth variables, income variables, and some demographic variables from the family files. Total household labor income is constructed as the sum of household wages and salaries and 50 percent of farm and business income. Then, to construct disposable labor income, we add transfers and subtract taxes, which we compute by using TAXSIM (version 9). For wealth, we use liquid wealth, which is defined as the sum of retirement accounts, checking and savings accounts, and other financial assets

Using the complete expenditure data set, we merge it with the tradability indices data set by UCC code.[16] We remove UCC expenditures associated with homeownership costs (mortgage interest, property taxes, and homeowner's and renter's insurance) and add the CEX variable for owner's equivalent rent, which we treat as a nontradable expenditure. For each household and interview period, we construct expenditures on tradables and nontradables as measured by the tradability indices, and merge this data set with the family files.

After the merge, we restrict the sample to households whose heads are between the ages of 25 and 64 and to households that have positive disposable labor income, wealth, and tradable and nontradable consumption, which leaves us with 23,484 household-year observations.

For generating graphs, we create binned scatter plots of tradable expenditure shares against wealth and disposable labor income deciles. For regression analysis, we take logs of wealth and disposable labor income. We perform a series of regressions with tradable expenditure share as the dependent variable. Regressors include log(wealth) and log(disposable labor income), along with fixed effects on year, age, household size, college graduation status, and homeownership.

[16]The tradability indices were obtained from Johnson (2017). A CEX expenditure category is classified as tradable if the input-output table commodity counterpart has a tradability share of at least 11 percent where tradability is defined as the maximum of imports and exports as a fraction of total commodity output.

A.2 Panel Survey of Income Dynamics (PSID)

We import demographic, income, wealth, and expenditure variables from PSID waves 2005 to 2015, so that we have data for years 2004, 2006, 2008, 2010, 2012, and 2014. As we do in the CEX, we construct total household labor income as the sum of household wages, salaries, bonus, and tips and 50 percent of farm and business income. Then, to construct disposable labor income, we add transfers and subtract taxes, which we compute by using TAXSIM (version 9).

We restrict the sample to households whose heads are between the ages of 25 and 64, and to households that have positive disposable labor income, wealth, and tradable and non-tradable consumption, which leaves us with 30,244 household-year observations. We then merge in average house prices and average rent values by state and census region from the Consumer Expenditure Survey, and use them to calculate home price-to-rent ratios for each state in each year. The price-rent ratios are then winsorized at the 1st and 99th percentiles. For homeowners, owner's equivalent rent is then calculated as the self-reported home value multiplied by the price-rent ratio. Total consumption is constructed as the sum of expenditures on child care, clothing, education, entertainment, food, health care, housing (except expenditures on mortgage, property taxes, and home and renter's insurance), transportation, and vacation, and in the case of homeowners, we add owner's equivalent rent. Tradable consumption is constructed as expenditures on clothing, food at home, prescriptions, home furnishings, the purchase and lease of cars and trucks, 22 percent of entertainment and vacation, and 21 percent of housing and vehicle repairs. The last two adjustments are made to reflect the fact that 22 percent of the expenditures on entertainment and vacation and 21 percent of housing and vehicle repair expenditures are tradable expenditures in the more disaggregated CEX. The tradable expenditure share is then obtained by dividing tradable consumption by total consumption.

For generating graphs, we create binned scatter plots of tradable expenditure share against wealth and income deciles. For regression analysis, we take logs of wealth and disposable labor income. We perform a series of regressions with the tradable expenditure share as the dependent variable. Regressors include log(wealth) and log(disposable labor income), along with fixed effects on year, age, household size, college graduation status, and homeownership.

A.3 Estimation of disposable income process

The estimation procedure closely follows the procedure described in Krueger et al. (2016) and Hur (2018). We use annual household income data from the PSID core sample (1970–1997), selecting all households whose head is aged between 23 and 64. For each household, we compute total household labor income as the sum of labor income of the head and spouse, 50 percent of income from farm and from business, plus transfers. Next, we construct household disposable labor income as total household labor income minus tax liabilities, computed for each household using the TAXSIM (ver 9) tax calculator. We then deflate disposable labor income using the CPI. On this sample, we regress the log real disposable income on age and year dummies. We then exclude all household income sequences that are are shorter than 5 years, leaving a final sample of 5278 households, with an average length of 17 years. On these data, we compute the autocovariance matrix of the residuals. The stochastic process in equation (26) is estimated using GMM, targeting the covariance matrix, where the weighting matrix is the identity matrix. We thank Chris Tonetti for providing the Matlab routines that perform the estimation.

B Sensitivity Analysis

Table 4 documents the robustness of the main empirical findings from Section 2. Columns (1) and (4) report the results for the PSID and CEX, respectively, for which all housing expenditures (rent, owner's equivalent rent, mortgage, property taxes, and renter's and homeowner's insurance) have been excluded. Column (2) reports, for the PSID, the case where all expenditures on entertainment, vacation, and housing and vehicle repairs are treated as nontradable expenditures. Columns (3) and (5) report the results for the PSID and CEX, respectively, with total labor income as the measure of income. Column (6) reports, for the CEX, the case for which we use an alternative measure of tradability. In particular, we define an expenditure item to be tradable if the sum of exports, direct imports, and indirect imports, exceed 25 percent of total output of that category. All regressions include year, age, household size, education, and homeowner fixed effects. The wealth coefficients remain statistically significant at the 1 percent level across specifications.

Table 4: Robustness of main empirical findings

	Tradable expenditure share (percent)					
	(1)	(2)	(3)	(4)	(5)	(6)
	PSID	PSID	PSID	CEX	CEX	CEX
	no housing	no partial adj.	total lab. inc.	no housing	total lab. inc.	alt. tradability
Wealth	–0.84***	–0.76***	–0.76***	–1.00***	–0.34***	–0.17***
	(0.07)	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)
Income	–2.14***	–0.66***	–0.41***	–2.50***	–1.03***	–0.24*
	(0.14)	(0.10)	(0.08)	(0.15)	(0.11)	(0.14)
N	30220	30228	28212	23387	21934	23484
Adj. R^2	0.047	0.079	0.072	0.254	0.167	0.163

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions include year, age, household size, education, and homeowner fixed effects.

C Computational Algorithm

The solution algorithm broadly consists of three steps:

1. Solve for a final steady state with low trade costs.

2. Solve for an initial steady state with high trade costs.

3. Solve for a transition path starting in (2) and ending in (1).

In each step, we solve the household problem over an unevenly spaced grid of 50 wealth points, k_{coarse}. To improve solution accuracy and to save time, we place more points near the borrowing constraint, where the household value function is more concave. We store the equilibrium wealth distribution as a histogram over an evenly spaced wealth grid of 5000 points, k_{fine}[17]. To improve precision, we set the maximum wealth level on k_{fine} much lower than the one on k_{coarse}. We check that this upper bound is not overly restrictive by verifying that the equilibrium distribution has no mass on the highest grid point at any point along the transition.

To calibrate, we guess a vector of parameters $[\beta, \tau, \gamma, \bar{c}, \theta]$. We then solve for the final and the initial steady state, calculate the model implied values for our targets, and update our guess using a quasi-Newton method with some dampening.

[17] For details on this method, see Young (2010)

C.1 Solving for a steady state

1. Let X^0 be an initial guess at the equilibrium level of aggregate investment, and $\mu_{init}(k, \varepsilon)$ an arbitrary initialization of the distribution over k_{fine} and $\mathcal{E}$.

2. Conditional on X^0, solve for the equilibrium rental rate, $r^\star(X^0)$.

   (a) Guess at $r^0(X^0)$.

   (b) Given $\{r^0(X^0), X^0\}$, use equations (20), (22), and the optimality conditions of the nontradables producer to get the other prices $\{w^0(r^0, X^0), P_X^0(r^0, X^0), P_T^0(r^0, X^0)\}$.

   (c) Now iterate on the Bellman equation until the value function converges to find the household value function and decision rules conditional on prices.

   (d) Use linear interpolation to map the value function and decision rules from k_{coarse} onto k_{fine}.

   (e) Beginning at μ_{init}, update the wealth distribution using the fine-grid decision rules for saving. Repeat until μ converges to $\mu^\star(r^0, X^0)$.

   (f) Use $\mu^\star$ and the fine-grid decision rules to compute all aggregates.

   (g) Find the implied interest rate, $\overline{r} = \frac{z_N}{P_N}\left(\frac{K_N^0}{L_N^0}\right)^{-\alpha_N}$.

   (h) We use Brent's Method to solve for $r^\star(X^0)$ over a fixed interval.

3. Once $r^\star(X^0)$ has been found, check that the absolute difference between the implied level of aggregate investment, $\overline{X}(r^\star, X^0)$, and X^0 is within some small tolerance. If so, then the steady state has been found at $(r^\star, X^\star)$. If not, then update the guess of aggregate investment according to a dampening rule, $X^1 = \zeta\overline{X} + (1-\zeta)X^0$ and repeat.

C.2 Solving for a transition path

Assume that the economy reaches its final steady state in $T+1$ periods.

1. Guess the sequence $\{r_t, X_t\}_{t=1}^T$. From this guess, we can compute the entire sequence of implied prices necessary to solve the household problem in each period.

2. Set V_{T+1} equal to the final steady state value function. Then, starting in period T, solve the Bellman equation backward using $V_{t+1}(k, \varepsilon)$ to find $V_t(k, \varepsilon)$. This produces a sequence of decision rules for periods $t = 1, .., T$.

3. Starting at $\mu^\star$ in the initial steady state, simulate forward using the household decision rules to find the sequence of wealth distributions from $t = 1, ..., T$. Along the way, solve for aggregate variables in each period.

4. Using the aggregates, find the market clearing values of $\{\overline{r}_t, \overline{X}_t\}_{t=1}^T$.

5. Check that the difference between the guess and the market clearing values (measured under the sup norm) is less than a small tolerance. If so, a transition path has been found.

6. If not, update the guess using a dampening method like the one described above and repeat.