Journal of International Economics 150 (2024) 103910

Contents lists available at ScienceDirect

Journal of International Economics

journal homepage: www.elsevier.com/locate/jie

Accounting for trade patterns☆

Stephen J. Redding[a,b,c], David E. Weinstein[d,*]

[a] Princeton University, JRR Building, Princeton, NJ 08544, United States of America
[b] NBER, United States of America
[c] CEPR, United Kingdom
[d] Columbia University and NBER, 420 W. 118th Street, MC 3308, New York, NY, 10027, United States of America

ARTICLE INFO

JEL classification:
F11
F12
F14

Keywords:
Comparative advantage
Trade
Prices
Quality
Variety

ABSTRACT

We develop a quantitative framework for decomposing trade patterns. We derive price indexes that determine comparative advantage and the aggregate cost of living. If firms and products are imperfect substitutes, we show that these price indexes depend on variety, average appeal (including quality), and the dispersion of appeal-adjusted prices. We show that they are only weakly related to standard empirical measures of average prices. We find that 40 percent of the cross-section variation in comparative advantage, and 90 percent of the time-series variation, is accounted for by variety and average appeal, with less than 10 percent attributed to average prices.

1. Introduction

Researchers in international trade are frequently concerned with understanding patterns of comparative advantage across countries and industries and movements in aggregate trade shares. Traditional theories, such as the Ricardian or Heckscher–Ohlin models, emphasize variation in exogenous determinants of unit costs and prices (such as technology and endowments). New trade theories, following Krugman (1980) and Helpman and Krugman (1985), highlight horizontal product differentiation and increasing returns to scale, such that the number of varieties produced affects the volume and pattern of trade. In contrast, heterogeneous firm theories, following Melitz (2003), suggest that the dispersion in productivity across firms within countries and industries can shape bilateral trade. Finally, another strand of research, including Khandelwal (2010) and Feenstra and Romalis (2014), points to the importance of product appeal and quality as a determinant of the intensity of international trade.

In quantifying the relative importance of these different forces, researchers face three key challenges. First, prices are not typically measured at the industry level, but are rather observed for thousands of disaggregated products within industries, which raises the challenge of how to aggregate from the product to the industry level. Second, product appeal is typically not directly measured, which raises the question of how to control for unobserved changes in the desirability and quality of products over time. Third, new

☆ We are grateful to the editor, two anonymous referees, Rob Feenstra, Keith Head, Pete Klenow, Kalina Manova, Thierry Mayer, Marc Melitz, Gianmarco Ottaviano and Daniel Xu for helpful comments. We would also like to thank colleagues and seminar participants at Bank of England, Carnegie-Mellon, Chicago, Columbia, Duke, NBER, Princeton, Stanford, UC Davis and UC Berkeley for helpful comments. Thanks to Patrick Farrell, Mark Greenan, Ildiko Magyari, Charly Porcher and Dyanne Vaught for outstanding research assistance. Redding and Weinstein thank Princeton and Columbia respectively for research support. Weinstein would also like to thank the National Science Foundation (NSF), United States of America (Award 1127493) for generous financial support. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the U.S. Census Bureau or any organization to which the authors are affiliated. Results have been screened to insure that no confidential data are revealed.

* Corresponding author.
E-mail addresses: reddings@princeton.edu (S.J. Redding), dew35@columbia.edu (D.E. Weinstein).

https://doi.org/10.1016/j.jinteco.2024.103910
Received 17 July 2022; Received in revised form 1 February 2024; Accepted 25 February 2024
Available online 5 March 2024

products enter and existing products exit, which raises the issue of how to appropriately weight the contribution of these entering and exiting products in understanding changes in comparative advantage and aggregate trade shares over time.

In this paper, we develop a quantitative framework for evaluating the relative contributions of prices, variety, producer heterogeneity and product appeal to the volume and pattern of international trade. Our framework is based on nested constant elasticity of substitution (CES) preferences and addresses each of the three challenges above. First, we aggregate from the prices of thousands of disaggregated Harmonized System (HS) products to compute theoretically-consistent price indexes at the industry and aggregate level. Therefore, our quantitative framework both rationalizes the observed disaggregated trade values and prices as equilibrium outcomes, but also preserves the ability to deliver sharp predictions for changes in industry comparative advantage and aggregate trade shares over time.

Second, we measure unobserved product appeal by inverting the CES demand system to recover the changes in appeal implied by the observed changes in prices and expenditure shares. Appeal is measured as a demand shifter that moves expenditure shares conditional on observed prices, as in the large empirical literature in industrial organization and international trade. Therefore, it captures both vertical differences across products (differences in quality) and horizontal differences across products (differences in other product characteristics). We show that this approach also controls for unobserved compositional changes within observed product categories. Hence, it can be implemented using unit values as measures of prices, as commonly available in trade datasets.

Third, we measure the contribution of entering and existing varieties to industry and aggregate price indexes using the Feenstra (1994) variety correction. Our approach thus simultaneously controls for changes in variety and appeal over time. Both our demand system inversion and the variety correction require estimates of elasticities of substitution. In our baseline specification, we estimate these elasticities using the reverse-weighting estimator of Redding and Weinstein (2023). But we demonstrate the robustness of our results to alternative elasticities, including those estimated using the generalized method of moments (GMM) estimator of Feenstra (1994) and Broda and Weinstein (2006). We demonstrate that our findings for prices, appeal and variety are robust across these alternative elasticities.

Our framework features a nested CES preference structure with sectors as our upper tier, firm divisions within sectors as our middle tier, and products within firm-sector divisions as our lower tier.[1] We develop a recursive estimation procedure for estimating the elasticities of substitution for each tier. In a first step, we estimate the elasticity of substitution across products within firm divisions (σ^U); invert the demand system to recover product appeal (φ_{ut}^U); and aggregate across products to compute a firm-division price index. In a second step, we use these price indexes to estimate the elasticity of substitution across firm divisions (σ^F); invert the demand system to recover firm-division appeal (φ_{ft}^F); and aggregate across firm divisions to compute a sectoral price index. In a third step, we use these sectoral price indexes to estimate the elasticity of substitution across sectors (σ^G); invert the demand system to recover sector appeal (φ_{gt}^G); and aggregate across sectors to compute an aggregate price index. Our approach uses only demand-side assumptions and conditions on the observed price and expenditure share data. Therefore, we remain agnostic about the supply-side of the economy, and the determinants of firm pricing and product introduction decisions.

We implement our approach using U.S. data from 1997–2011 (reported in the main paper) and Chilean data from 2007–14 (reported in the Online Appendix). We demonstrate the same qualitative and quantitative pattern of results in both contexts. In both cases, we find that products within firm divisions, firm divisions within sectors, and sectors are imperfect substitutes for one another. Using our U.S. data, we estimate a median elasticity of substitution across products of 6.29, a median elasticity across firm divisions of 2.66, and an elasticity across sectors of 1.36. We show that the special cases of our framework in which the sector or firm division nests are absent are strongly rejected at conventional significance levels.

We use our nested CES preference structure to define a measure of revealed comparative advantage (RCA) that depends on relative price indexes across countries within sectors. We show that these country price indexes are themselves aggregations of the price indexes for each firm division from that country within that sector. We show that both RCA and these country price indexes can be exactly decomposed into the contributions of entry/exit, average prices, average appeal; and a heterogeneity term that captures the dispersion of appeal-adjusted prices. The greater the dispersion of appeal-adjusted prices within a country-sector, the lower the price index for that country-sector, because goods are substitutes. Therefore, greater dispersion in appeal-adjusted prices enhances the ability of consumers to substitute towards goods with lower appeal-adjusted prices.

We show that much of the observed variation in comparative advantage is driven by variety, heterogeneity and appeal. Firm entry/exit and the dispersion in appeal-adjusted prices each account for around one third of the cross-section variation in patterns of trade across countries and sectors. By contrast, average appeal and average prices contribute just over 20 percent and just under 10 percent, respectively. For changes in trade patterns over time, the results are even more stark. Firm entry/exit and average appeal each account for around 45 percent of the variation, with the dispersion of appeal-adjusted prices making up most of the rest. We demonstrate that this pattern is robust across alternative values for the elasticities of substitution. Indeed, for parameter values for which goods are imperfect substitutes, the contributions from firm entry/exit and the dispersion of appeal-adjusted prices to patterns of trade are invariant to these assumed elasticities. This pattern of results suggests that comparative advantage does not only operate through prices and unit costs, as in traditional trade theories. Instead, comparative advantage is heavily influenced by firm and product variety and heterogeneity across and within firms, as for example in models that combine product differentiation, increasing returns and producer heterogeneity together with the forces emphasized by traditional trade theory (e.g., Bernard et al. (2007b, 2011).

[1] We use the term "firm divisions" within sectors because a given firm can both supply multiple products within sectors and operate in multiple sectors, as in the literature on multiple product firms, including Feenstra and Ma (2008), Bernard et al. (2010, 2011), Eckel and Peter Neary (2010), and Dhingra (2013).

We also find that the non-conventional forces of variety, appeal and the dispersion appeal-adjusted prices are important for understanding aggregate U.S. import shares for its largest trade partners. Most of the increase in China's share of aggregate U.S. imports over our sample period occurs through increases in the number of varieties, average firm appeal and the dispersion in appeal-adjusted prices. In contrast, average product prices increased more rapidly for China than the other countries in our sample, which acted to reduce China's aggregate market share. Therefore, the reasons for the explosive growth of Chinese exports were not cheaper Chinese exports, but rather substantial firm entry (variety), appeal upgrading, and improvements in the performance of leading firms relative to lagging firms (the dispersion of appeal-adjusted prices). As for comparative advantage above, we find that most of the change in countries' aggregate shares of U.S. imports is explained by forces other than the average prices and unit costs emphasized by traditional theories of international trade.

Finally, we also decompose import price indexes into the same four components of average prices, average appeal, entry/exit (variety), and the dispersion in appeal-adjusted prices (heterogeneity). We show that the average price term has a similar functional form to the Bureau of Labor Statistics (BLS) import price index and tracks this official index closely in the data (with a correlation coefficient of 0.72), even though we measure prices using unit values rather than price quotes. Nevertheless, the large contributions from variety, average appeal and the heterogeneity in appeal-adjusted prices imply that the BLS import price index has little correlation with the theoretically-consistent import price index.

In arriving at these findings, we make a number of other methodological contributions. First, our approach can be implemented even if observed products are aggregations of the true products over which consumer preferences are defined. We show that our measures of appeal not only capture differences in quality and other product characteristics but also unobserved differences in composition within observed product categories. Second, our methods can be used even if disaggregated data on product prices are only available for foreign goods within sectors and not for domestic goods. We demonstrate that the observed shares of expenditure on foreign products within sectors can be used to control for the unobserved domestic prices.

Third, our framework can be applied even if some sectors are non-traded and disaggregated data on product prices are not available for these non-traded sectors. In this case, the observed share of expenditure on traded sectors can be used to control for the unobserved non-traded prices. Fourth, unobserved appeal in each nest of utility only can be identified up to a normalization or choice of units. But our decompositions of RCA only depends on the relative values of appeal across countries. Therefore, this normalization or choice of units cancels out from the numerator and denominator of these relative comparisons.

Our paper is related to several strands of existing research. First, we build on a long tradition in international trade that examines how to develop measures of prices in which quality and/or variety are changing (Feenstra, 1994; Hallak and Schott, 2011; Feenstra and Romalis, 2014). Our approach builds on Hottman et al. (2016), which provides evidence on the sources of differences in firm size within sectors using barcode data for grocery products. We use the CES unified price index (CUPI) from Redding and Weinstein (2020) within our nested demand structure. Relative to those two papers, our main contributions are as follows. First, we define a measure of revealed comparative advantage that can be exactly decomposed into the contributions of different theoretical mechanisms in leading theories of international trade. Second, we show how to aggregate price data for thousands of disaggregated foreign products to aggregate price indexes for the economy as a whole, even without price data for domestic products within traded sectors or for non-traded sectors.

Second, our paper is related to the literature estimating elasticities of substitution between varieties and quantifying the contribution of new goods to welfare. As shown in Feenstra (1994), the contribution of entry and exit to the change in the CES price index can be captured using the expenditure share on common products (supplied in both periods) and the elasticity of substitution. Building on this approach, Broda and Weinstein (2006) quantify the contribution of international trade to welfare through an expansion on the number of varieties, and Broda and Weinstein (2010) examine product creation and destruction over the business cycle. Other related research using scanner data to quantify the effects of globalization includes Handbury (2021), Atkin and Donaldson (2015), Atkin et al. (2018), and Faber and Fally (2022). Whereas this existing research assumes that appeal is constant for each surviving variety, we show that allowing for time-varying appeal is central to rationalizing aggregate and disaggregate patterns of trade.

Third, our research relates to the broader literature on comparative advantage in international trade. Research in this area traditionally makes strong functional form assumptions about demand or supply in order to derive sharp theoretical predictions. As one approach to relaxing these functional form assumptions, Adão et al. (2017) consider exchange economies with mixed CES factor demand, which allows for differences across groups in elasticities of substitution. As another approach, Adão et al. (2020) assume CES demand, but consider non-parametric productivity distributions on the supply-side. We assume CES preferences, but allow for rich substitution patterns because of the presence of multiple CES nests, and we remain agnostic about the supply-side of the economy. Using only demand-side assumptions, we show how to aggregate the observed data on prices and expenditure shares for thousands of foreign products to compute industry and aggregate price indexes. We decompose changes in industry comparative advantage and aggregate trade shares into the contributions of variety (entry/exit), average appeal, average prices, and the dispersion in appeal-adjusted prices (heterogeneity). Through remaining agnostic about the supply-side of the economy, our approach encompasses non-neoclassical models with imperfect competition and increasing returns to scale, including Krugman (1980), Melitz (2003), and Atkeson and Burstein (2008).

The remainder of the paper is structured as follows. Section 2 introduces our theoretical framework. Section 3 outlines our structural estimation approach. Section 4 discusses our data. Section 5 reports our empirical results. Section 6 concludes. An Online Appendix contains technical derivations, additional empirical results for the U.S., and a replication of our U.S. results using Chilean data.

2. Theoretical framework

We begin by showing that our framework exactly rationalizes observed micro trade data and permits exact aggregation, so that it can be used to quantify the importance of different micro mechanisms for macro variables. We assume CES preferences as the leading demand system in international trade, with a nesting structure guided by existing trade theories, which distinguish sectors, countries, firms and products. In this section, we take the elasticity of substitution in each nest as known, and use observed expenditure share and price data to solve for the unobserved values of appeal (up to a normalization or choice of units) that exactly rationalize the observed data as an equilibrium outcome. In Section 3 below, we show how to estimate the elasticities of substitution in each nest.

We index importing countries ("importers") by j and exporting countries ("exporters") by i (where each country can buy its own output). Each exporter can supply goods to each importer in a number of sectors that we index by g (a mnemonic for "group"). We denote the set of sectors by Ω^G and we indicate the number of elements in this set by N^G. We denote the set of countries from which importer j sources goods in sector g at time t by Ω^I_{jgt} and we indicate the number of elements in this set by N^I_{jgt}. Each sector (g) in each exporter (i) is comprised of firms, indexed by f (a mnemonic for "firm"). We denote the set of firms in sector g that export from country i to country j at time t by Ω^F_{jigt}; and we indicate the number of elements in this set by N^F_{jigt}. Each active firm can supply one or more products that we index by u (a mnemonic for "unit", as our most disaggregated unit of analysis); we denote the set of products supplied by firm f at time t by Ω^U_{ft}; and we indicate the number of elements in this set by N^U_{ft}.[2]

2.1. Demand

The aggregate unit expenditure function for importer j at time t (P_{jt}) is defined over the sectoral price index (P^G_{jgt}) and appeal parameter (φ^G_{jgt}) for each sector $g \in \Omega^G$:

$$P_{jt} = \left[\sum_{g \in \Omega^G} \left(P^G_{jgt} / \varphi^G_{jgt} \right)^{1-\sigma^G} \right]^{\frac{1}{1-\sigma^G}}, \qquad \sigma^G > 1, \varphi^G_{jgt} > 0, \tag{1}$$

where σ^G is the elasticity of substitution across sectors and φ^G_{jgt} captures the relative appeal for each sector. The unit expenditure function for each sector g depends on the price index (P^F_{ft}) and appeal parameter (φ^F_{ft}) for each firm $f \in \Omega^F_{jigt}$ from each exporter $i \in \Omega^I_{jgt}$ within that sector:

$$P^G_{jgt} = \left[\sum_{i \in \Omega^I_{jgt}} \sum_{f \in \Omega^F_{jigt}} \left(P^F_{ft} / \varphi^F_{ft} \right)^{1-\sigma^F_g} \right]^{\frac{1}{1-\sigma^F_g}}, \qquad \sigma^F_g > 1, \varphi^F_{ft} > 0, \tag{2}$$

where σ^F_g is the elasticity of substitution across firms f for sector g and φ^F_{ft} controls the relative appeal for each firm within that sector. We assume that the unit expenditure function within each sector takes the same form for both final consumption and intermediate use, so that we can aggregate both these sources of expenditure, as in Eaton and Kortum (2002) and Caliendo and Parro (2015).

We allow firm varieties to be horizontally differentiated and assume the same elasticity of substitution for domestic and foreign firms within sectors (σ^F_g).[3] The unit expenditure function for each firm f depends on the price (P^U_{ut}) and appeal parameter (φ^U_{ut}) for each product $u \in \Omega^U_{ft}$ supplied by that firm:

$$P^F_{ft} = \left[\sum_{u \in \Omega^U_{ft}} \left(P^U_{ut} / \varphi^U_{ut} \right)^{1-\sigma^U_g} \right]^{\frac{1}{1-\sigma^U_g}}, \qquad \sigma^U_g > 1, \varphi^U_{ut} > 0, \tag{3}$$

where σ^U_g is the elasticity of substitution across products within firms for sector g and φ^U_{ut} captures the relative appeal for each product within a given firm.

A few remarks about this specification are useful. First, we allow prices to vary across products, firms, sectors and countries, which implies that our setup nests models in which relative and absolute production costs differ within and across countries. Second, for notational convenience, we define the firm index $f \in \Omega^F_{jigt}$ by sector g, destination country j and source country i. Therefore, if a firm has operations in multiple sectors and/or exporting countries, we label these different divisions separately. As we observe the prices of the products for each firm, sector and exporting country in the data, we do not need to take a stand on market structure or the level at which product introduction and pricing decisions are made within the firm.

[2] We use the superscript G to denote a sector-level variable, the superscript F to represent a firm-level variable, and the superscript U to indicate a product-level variable. We use subscripts j and i to index individual countries, the subscript g to reference individual sectors, the subscript f to refer to individual firms, the subscript u to label individual products, and the subscript t to indicate time.

[3] Therefore, we associate horizontal differentiation within sectors with firm brands, which implies that differentiation across countries emerges solely because there are different firms in different countries, as in Krugman (1980) and Melitz (2003). It is straightforward to also allow the elasticity of substitution to differ between home and foreign firms, which introduces separate differentiation by country, as in Armington (1969). Feenstra et al. (2018) find that they often cannot reject the same elasticity between home and foreign varieties as between foreign varieties.

Third, the fact that the elasticities of substitution across products within firms (σ_g^U), across firms within sectors (σ_g^F), and across sectors within countries (σ^G) need not be infinite implies that our framework nests models in which products are differentiated within firms, across firms within sectors, and across sectors. Moreover, our work is robust to collapsing one or more of these nests. For example, if all three elasticities are equal ($\sigma_g^U = \sigma_g^F = \sigma^G$), all three nests collapse, and the model becomes equivalent to one in which consumers only care about firm varieties. Alternatively, if $\sigma_g^U = \sigma_g^F = \infty$ and $\sigma^G < \infty$, only sectors are differentiated, and varieties are perfectly substitutable within sectors. Finally, if $\sigma_g^U = \sigma_g^F > \sigma^G$, firm brands are irrelevant, so that products are equally differentiated within and across firms for a given sector.

Fourth, the appeal parameters (φ_{jgt}^G, φ_{ft}^F, φ_{ut}^U) capture anything that shifts the demand for sectors, firms and products *conditional* on price. Therefore, they incorporate both vertical differences across products (differences in quality) and horizontal differences across products (differences in other product characteristics). We refer to these demand shifters as appeal to make clear that they capture both sources of differences in product characteristics.[4] We show below how to recover these demand shifters from the observed price and expenditure share data up to a normalization or choice of units. We use the normalization that the geometric mean of the demand shifters in each nest of utility is equal to one. We show below that our decompositions of revealed comparative advantage (RCA) only depend on the *relative* values of appeal across countries. Therefore, the normalization or choice of units for appeal cancels out from the numerator and denominator of these relative comparisons.

Finally, in order to simplify notation, we suppress the subscript for importer j, exporter i, and sector g for firm and product appeal (φ_{ft}^F, φ_{ut}^U). However, we take it as understood that we allow these demand shifters for a given firm f and product u to vary across importers j, exporters i and sectors g, which captures the idea that a firm's varieties can be more appealing in some markets than others. For example, Sony products may be more appealing to Americans than Chileans, or may have more consumer appeal in the television sector than the camera sector, or even may be perceived to have higher quality if they are supplied from Japan rather than from another location.

2.2. Non-traded sectors

We allow some sectors to be non-traded, in which case we do not observe products within these sectors in our disaggregated import transactions data, but we can measure total expenditure on these non-traded sectors using domestic expenditure data. We incorporate these non-traded sectors by re-writing the overall unit expenditure function in Eq. (1) in terms of the share of expenditure on tradable sectors (μ_{jt}^T) and a unit expenditure function for these tradable sectors ($\mathbb{P}_{jt}^T$):

$$P_{jt} = \left(\mu_{jt}^T\right)^{\frac{1}{\sigma^G-1}} \mathbb{P}_{jt}^T. \tag{4}$$

The share of expenditure on the set of tradable sectors $\Omega^T \subseteq \Omega^G$ (μ_{jt}^T) can be measured using aggregate data on expenditure in each sector:

$$\mu_{jt}^T \equiv \frac{\sum_{g\in\Omega^T} X_{jgt}^G}{\sum_{g\in\Omega^G} X_{jgt}^G} = \frac{\sum_{g\in\Omega^T}\left(P_{jgt}^G/\varphi_{jgt}^G\right)^{1-\sigma^G}}{\sum_{g\in\Omega^G}\left(P_{jgt}^G/\varphi_{jgt}^G\right)^{1-\sigma^G}}, \tag{5}$$

where X_{jgt}^G is total expenditure by importer j on sector g at time t. The unit expenditure function for *tradable* sectors ($\mathbb{P}_{jt}^T$) depends on the price index for each tradable sector (P_{jgt}^G):

$$\mathbb{P}_{jt}^T \equiv \left[\sum_{g\in\Omega^T}\left(P_{jgt}^G/\varphi_{jgt}^G\right)^{1-\sigma^G}\right]^{\frac{1}{1-\sigma^G}}, \tag{6}$$

where we use the "blackboard" font $\mathbb{P}$ to denote price indexes that are defined over tradable goods.

Therefore, our assumption of CES preferences allows us to construct an overall price index without observing entry, exit, sales, prices or quantities of individual products in non-tradable sectors. From Eq. (5), there is always a one-to-one mapping between the market share of tradable sectors and the relative price indexes in the two sets of sectors. In particular, if the price of non-tradables relative to tradables rises, the expenditure *share* of tradables (μ_{jt}^T) also rises if demand is elastic. In other words, the share of tradables is a sufficient statistic for understanding the relative prices of tradables and non-tradables. As one can see from Eq. (4), if we hold fixed the price of tradables ($\mathbb{P}_{jt}^T$), a rise in the share of tradables (μ_{jt}^T) can only occur under elastic demand if the price of non-tradables sectors also rises, which means that the aggregate price index index (P_{jt}) must also be increasing in the share of tradables.

2.3. Domestic versus foreign varieties within tradable sectors

We also allow for domestic varieties within tradable sectors, in which case we again do not observe them in our import transactions data, but we can back out the implied expenditure on these domestic varieties using data on domestic shipments,

[4] See, for example, the discussion in Di Comite et al. (2014). A large literature in international trade has interpreted these demand shifters as capturing product quality, including Schott (2004), Khandelwal (2010), Hallak and Schott (2011), Feenstra and Romalis (2014) and Sutton and Trefler (2016).

exports and imports for each tradable sector. We incorporate domestic varieties within tradable sectors by re-writing the sectoral price index in Eq. (2) in terms of the share of expenditure on foreign varieties within each sector (the sectoral import share μ^G_{jgt}) and a unit expenditure function for these foreign varieties (a sectoral import price index $\mathbb{P}^G_{jgt}$):

$$P^G_{jgt} = \left(\mu^G_{jgt}\right)^{\frac{1}{\sigma^F_g - 1}} \mathbb{P}^G_{jgt}. \tag{7}$$

The sectoral import share (μ^G_{jgt}) equals total expenditure on imported varieties within a sector divided by total expenditure on that sector:

$$\mu^G_{jgt} \equiv \frac{\sum_{i \in \Omega^E_{jgt}} \sum_{f \in \Omega^F_{jigt}} X^F_{ft}}{X^G_{jgt}} = \frac{\sum_{i \in \Omega^E_{jgt}} \sum_{f \in \Omega^F_{jigt}} \left(P^F_{ft}/\varphi^F_{ft}\right)^{1-\sigma^F_g}}{\sum_{i \in \Omega^I_{jgt}} \sum_{f \in \Omega^F_{jigt}} \left(P^F_{ft}/\varphi^F_{ft}\right)^{1-\sigma^F_g}}, \tag{8}$$

where $\Omega^E_{jgt} \equiv \left\{ \Omega^I_{jgt} : i \neq j \right\}$ is the subset of *foreign* countries $i \neq j$ that supply importer j within sector g at time t; X^F_{ft} is expenditure on firm f; and X^G_{jgt} is country j's total expenditure on all firms in sector g at time t. The sectoral import price index ($\mathbb{P}^G_{jgt}$) is defined over the foreign goods observed in our disaggregated import transactions data as:

$$\mathbb{P}^G_{jgt} \equiv \left[\sum_{i \in \Omega^E_{jgt}} \sum_{f \in \Omega^F_{jigt}} \left(P^F_{ft}/\varphi^F_{ft}\right)^{1-\sigma^F_g} \right]^{\frac{1}{1-\sigma^F_g}}. \tag{9}$$

In this case, the import share within each sector is the appropriate summary statistic for understanding the relative prices of home and foreign varieties within that sector. From Eq. (7), the sectoral price index (P^G_{jgt}) is *increasing* in the sectoral *foreign* expenditure share (μ^G_{jgt}) if demand is elastic. The reason is that our expression for the sectoral price index (P^G_{jgt}) conditions on the price of foreign varieties, as is captured by the import price index ($\mathbb{P}^G_{jgt}$). For a given value of this import price index, a higher foreign expenditure share (μ^G_{jgt}) implies that domestic varieties are less attractive under elastic demand, which implies a higher sectoral price index.[5]

2.4. Exporter price indexes

To examine the contribution of individual countries to trade patterns and aggregate prices, it proves convenient to rewrite the sectoral import price index ($\mathbb{P}^G_{jgt}$) in Eq. (9) in terms of price indexes for each foreign exporting country within that sector ($\mathbb{P}^E_{jigt}$):

$$\mathbb{P}^G_{jgt} = \left[\sum_{i \in \Omega^E_{jgt}} \left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g} \right]^{\frac{1}{1-\sigma^F_g}}, \tag{10}$$

where importer j's price index for exporter i in sector g at time t ($\mathbb{P}^E_{jigt}$) is defined over the firm price indexes (P^F_{ft}) and appeal (φ^F_{ft}) for each of the firms f from that foreign exporter and sector:

$$\mathbb{P}^E_{jigt} \equiv \left[\sum_{f \in \Omega^F_{jigt}} \left(P^F_{ft}/\varphi^F_{ft}\right)^{1-\sigma^F_g} \right]^{\frac{1}{1-\sigma^F_g}}, \tag{11}$$

and we use the superscript E to denote a variable for a *foreign* exporting country.

This exporter price index (11) is a key object in our empirical analysis, because it summarizes importer j's cost of sourcing goods from exporter i within sector g at time t. We show below that the relative values of these exporter price indexes across countries and sectors determine comparative advantage. Note that substituting this definition of the exporter price index (11) into the sectoral import price index (10), we recover our earlier equivalent expression for the sectoral import price index in Eq. (9).

2.5. Expenditure shares

Using the properties of CES demand, the share of each product in expenditure on each firm (S^U_{ut}) is given by:

$$S^U_{ut} = \frac{\left(P^U_{ut}/\varphi^U_{ut}\right)^{1-\sigma^U_g}}{\sum_{\ell \in \Omega^U_{ft}} \left(P^U_{\ell t}/\varphi^U_{\ell t}\right)^{1-\sigma^U_g}}, \tag{12}$$

[5] In contrast, the expression for the price index in Arkolakis et al. (2012) conditions on the price of *domestically-produced* varieties, and is *increasing* in the *domestic* expenditure share. The intuition is analogous. For a given price of domestically-produced varieties, a higher domestic trade share implies that foreign varieties are less attractive under elastic demand, which implies a higher price index.

where the firm and sector expenditure shares are defined analogously.

In the data, we observe product expenditures (X^U_{ut}) and quantities (Q^U_{ut}) for each product category. In our baseline specification in the paper, we assume that the level of disaggregation at which products are observed in the data corresponds to the level at which firms make product decisions. Therefore, we measure prices using unit values ($P^U_{ut} = X^U_{ut}/Q^U_{ut}$). In Section A.7 of the Online Appendix, we show that our analysis generalizes to the case in which firms supply products at a more disaggregated level than the categories observed in the data. In this case, there can be unobserved differences in composition within observed product categories. We show that these unobserved compositional differences enter the model in exactly the same way as unobserved differences in appeal for each observed product category. Therefore, our analysis continues to hold, but some of what we label product appeal may reflect compositional changes at a more disaggregate level than we can observe in the data.

2.6. Model inversion

Given the observed data on prices and expenditures for each product $\{P^U_{ut}, X^U_{ut}\}$ and the substitution parameters $\{\sigma^U_g, \sigma^F_g, \sigma^G\}$, we now show how to invert the model to recover unique values for appeal (up to a normalization or choice of units). Dividing the share of a product in firm expenditure (12) by its geometric mean across common products within that firm, product appeal can be expressed as the following function of data and parameters:

$$\frac{\varphi^U_{ut}}{\mathbb{M}^{U*}_{ft}\left[\varphi^U_{ut}\right]} = \frac{P^U_{ut}}{\mathbb{M}^{U*}_{ft}\left[P^U_{ut}\right]}\left(\frac{S^U_{ut}}{\mathbb{M}^{U*}_{ft}\left[S^U_{ut}\right]}\right)^{\frac{1}{\sigma^U_g-1}}. \tag{13}$$

where $\mathbb{M}[\cdot]$ is the geometric mean operator such that $\mathbb{M}^{U*}_{ft}\left[\varphi^U_{ut}\right] \equiv \left(\prod_{u\in\Omega^U_{ft,t-1}}\varphi^U_{ut}\right)^{1/N^U_{t,t-1}}$; and we choose units in which to measure product appeal such that its geometric mean across common products within each firm is equal to one: $\mathbb{M}^{U*}_{ft}\left[\varphi^U_{ut}\right] = 1$.

Having solved for product appeal (φ^U_{ut}) using Eqs. (13) and our normalization, we use Eq. (3) to compute the firm price index, as reproduced below. Using this solution for the firm price index (P^F_{ft}) from Eq. (3), we divide the share of a foreign firm in sectoral imports by its geometric mean across common foreign firms within that sector to obtain the following solution for appeal for each foreign firm:

$$\frac{\varphi^F_{ft}}{\mathbb{M}^{F*}_{jgt}\left[\varphi^F_{ft}\right]} = \frac{P^F_{ft}}{\mathbb{M}^{F*}_{jgt}\left[P^F_{ft}\right]}\left(\frac{\mathrm{S}^F_{ft}}{\mathbb{M}^{F*}_{jgt}\left[\mathrm{S}^F_{ft}\right]}\right)^{\frac{1}{\sigma^F_g-1}}, \tag{14}$$

where we choose units in which to measure firm appeal such that its geometric mean across common foreign firms within each sector is equal to one: $\mathbb{M}^{F*}_{jgt}\left[\varphi^F_{ft}\right] \equiv \left(\prod_{i\in\Omega^E_{jgt,t-1}}\prod_{f\in\Omega^F_{jigt,t-1}}\varphi^F_{ft}\right)^{\frac{1}{N^F_{jgt,t-1}}} = 1$.

Having solved for firm appeal (φ^F_{ft}) for each foreign firm using equations, we use Eqs. (7) and (9) to compute the sector price index. Using this solution for the sector price index (P^G_{jgt}), we divide the share of an individual tradable sector in all expenditure on tradable sectors by its geometric mean across these tradable sectors to obtain the following solution for sector appeal for each tradable sector:

$$\frac{\varphi^G_{jgt}}{\mathbb{M}^T_{jt}\left[\varphi^G_{jgt}\right]} = \frac{P^G_{jgt}}{\mathbb{M}^T_{jt}\left[P^G_{jgt}\right]}\left(\frac{\mathrm{S}^T_{jgt}}{\mathbb{M}^T_{jt}\left[\mathrm{S}^T_{jgt}\right]}\right)^{\frac{1}{\sigma^G-1}}, \tag{15}$$

where we choose units in which to measure sector appeal such that its geometric mean across tradable sectors is equal to one: $\mathbb{M}^T_{jt}\left[\varphi^G_{jgt}\right] \equiv \left(\prod_{g\in\Omega^T}\varphi^G_{jgt}\right)^{\frac{1}{N^T}} = 1$. Recall that there is no asterisk in the superscript of the geometric mean operator across tradable sectors, because the set of tradable sectors is constant over time.

Having solved for sector appeal (φ^G_{jgt}) for each tradable sector, we use Eqs. (4) and (6) in the paper to compute the aggregate price index, as reproduced below:

$$P_{jt} = \left(\mu^T_{jt}\right)^{\frac{1}{\sigma^G-1}}\left[\sum_{g\in\Omega^T}\left(P^G_{jgt}/\varphi^G_{jgt}\right)^{1-\sigma^G}\right]^{\frac{1}{1-\sigma^G}}, \tag{16}$$

where recall that μ^T_{jt} the observed share of aggregate expenditure on tradable sectors.

Given the observed data on prices and expenditures $\{P^U_{ut}, X^U_{ut}\}$ and the substitution parameters $\{\sigma^U_g, \sigma^F_g, \sigma^G\}$, no supply-side assumptions are needed to undertake this analysis and recover the structural residuals $\{\varphi^U_{ut}, \varphi^F_{ft}, \varphi^G_{jgt}\}$. The reason is that we observe both prices (P^U_{ut}) and expenditures (X^U_{ut}). Therefore, we do not need to take a stand on the different supply-side forces that determine these observed prices and expenditure shares. Under our normalizations, product appeal (φ^U_{ut}) captures the relative appeal of products within foreign firms; firm appeal (φ^F_{ft}) reflects the relative appeal of foreign firms within sectors; and sector appeal (φ^G_{jgt}) captures the relative appeal of tradable sectors.

An important difference between our approach and standard exact price indexes for CES is that we allow the appeal parameters to change over time. This difference is an important advantage for empirical applications using Harmonized System (HS) product categories, where it is plausible that substantial changes in relative quality can occur over time for individual product categories, firms, countries and sectors. For example, the relative quality of the cars supplied by Japanese manufacturers to the United States arguably improved substantially between the 1960s and 2000s. Our framework captures quality upgrading for individual foreign products (changes in φ^U_{ut}) for individual foreign firms (changes in φ^F_{ft}) and for individual tradable sectors (changes in φ^G_{jgt}). We also allow for proportional changes in the quality for all foreign varieties relative to all domestic varieties within each sector, which are implicitly captured in the shares of expenditure on foreign varieties within sectors (μ^G_{jgt}) in Eq. (7) for the sectoral price index (P^G_{jgt}). Similarly, we allow for proportional changes in the quality for all tradable sectors relative to all non-tradable sectors, which are implicitly captured in the share of expenditure on tradable sectors (μ^T_{jt}) in Eq. (4) for the aggregate price index (P_{jt}).

2.7. Log-linear CES price index

We now use the CES expenditure share to rewrite the CES price index in an exact log linear form that enables us to aggregate from micro to macro. We illustrate our approach using the product expenditure share within the firm tier of utility, but the analysis is analogous for each of the other tiers of utility. Rearranging the expenditure share of products within firms (12) using the firm price index (3), we obtain:

$$P^F_{ft} = \frac{P^U_{ut}}{\varphi^U_{ut}} \left(S^U_{ut}\right)^{\frac{1}{\sigma^U_g - 1}}, \tag{17}$$

which must hold for each product $u \in \Omega^U_{ft}$. Taking logarithms, averaging across products within firms, and adding and subtracting $\frac{1}{\sigma^U_g - 1} \ln N^U_{ft}$, we obtain the following exact log linear decomposition of the CES price index into four terms:

$$\ln P^F_{ft} = \underbrace{\mathbb{E}^U_{ft}\left[\ln P^U_{ut}\right]}_{\text{(i) Average log prices}} - \underbrace{\mathbb{E}^U_{ft}\left[\ln \varphi^U_{ut}\right]}_{\text{(ii) Average log appeal}} + \underbrace{\frac{1}{\sigma^U_g - 1}\left(\mathbb{E}^U_{ft}\left[\ln S^U_{ut}\right] - \ln \frac{1}{N^U_{ft}}\right)}_{\text{(iii) Dispersion appeal-adjusted prices}} - \underbrace{\frac{1}{\sigma^U_g - 1} \ln N^U_{ft}}_{\text{(iv) Variety}}, \tag{18}$$

where $\mathbb{E}[\cdot]$ denotes the mean operator such that $\mathbb{E}^U_{ft}\left[\ln P^U_{ut}\right] \equiv \frac{1}{N^U_{ft}} \sum_{u\in\Omega^U_{ft}} \ln P^U_{ut}$; the superscript U indicates that the mean is taken across products;[6] and the subscripts f and t indicate that this mean varies across firms and over time.[7]

In general, there are many different ways of writing the CES price index, but the expression in terms of geometric means in Eq. (18) has three key advantages for our empirical analysis. First, it permits an exact additive decomposition into the contributions of the different mechanisms emphasized in leading theories of international trade (prices, variety, appeal and heterogeneity). Second, it is robust to measurement error that is mean zero in logs, which averages out when we take means in logs across goods.

Third, it has an intuitive economic interpretation. When products are perfect substitutes ($\sigma^U_g \to \infty$), the average of log appeal-adjusted prices ($\mathbb{E}^U_{ft}\left[\ln\left(P^U_{ut}/\varphi^U_{ut}\right)\right]$) is a sufficient statistic for the log firm price index (as captured by terms (i) and (ii)). The reason is that perfect substitutability implies the equalization of appeal-adjusted prices for all consumed varieties ($P^U_{ut}/\varphi^U_{ut} = P^U_{\ell t}/\varphi^U_{\ell t}$ for all $u, \ell \in \Omega^U_{ft}$ as $\sigma^U_g \to \infty$). Therefore, the mean of log appeal-adjusted prices is equal to the log appeal-adjusted prices for each product ($\mathbb{E}^U_{ft}\left[\ln\left(P^U_{ut}/\varphi^U_{ut}\right)\right] = \ln\left(P^U_{\ell t}/\varphi^U_{\ell t}\right)$ for all $u, \ell \in \Omega^U_{ft}$ as $\sigma^U_g \to \infty$).

In contrast, when products are imperfect substitutes ($1 < \sigma^U_g < \infty$), the firm price index also depends on both the number of varieties (term (iv)) and the dispersion of appeal-adjusted prices across those varieties (term (iii)). The contribution from the number of varieties reflects consumer love of variety: if varieties are imperfect substitutes ($1 < \sigma^U_g < \infty$), an increase in the number of products sold by a firm (N^U_{ft}) reduces the firm price index. Keeping constant the price-to-appeal ratio of each variety, consumers obtain more utility from firms that supply more varieties than others.

The contribution from the dispersion of appeal-adjusted prices also reflects imperfect substitutability. If all varieties have the same appeal-adjusted price, they all have the same expenditure share ($S^U_{ut} = 1/N^U_{ft}$). At this point, the mean of log-expenditure shares is maximized, and this third term is equal to zero. Moving away from this point and increasing the dispersion of appeal-adjusted prices, by raising the appeal-adjusted price for some varieties and reducing it for others, the dispersion of expenditure shares across varieties increases. As the log function is strictly concave, this increased dispersion of expenditure shares in turn implies a fall in the mean of log expenditure shares. Hence, this third term is negative when appeal-adjusted prices differ across varieties ($\mathbb{E}^U_{ft}\left[\ln S^U_{ut}\right] < \ln\left(1/N^U_{ft}\right)$), which reduces the firm price index. Intuitively, holding constant average appeal-adjusted prices, consumers prefer to source products from firms with more dispersed appeal-adjusted prices, because they can substitute away from products with high appeal-adjusted prices and towards those with low appeal-adjusted prices.

[6] Recall that our normalization in equation (A.2.4) implies that the average log common-product appeal within foreign firms is equal to zero: $\mathbb{E}^{U*}_{ft}\left[\ln \varphi^U_{ut}\right] = 0$.

[7] This price index in Eq. (18) uses a different but equivalent expression for the CES price index from Hottman et al. (2016), in which the dispersion of sales across goods is captured using a different term from $\left(1/\left(\sigma^U_g - 1\right)\right) \mathbb{E}^U_{ft}\left[\ln S^U_{ut}\right]$.

2.8. Entry, exit and the unified price index

One challenge in implementing this exact aggregation approach is the entry and exit of varieties over time in the micro data. To correctly take account of entry and exit between each pair of time periods, we follow Feenstra (1994) in using the share of expenditure on "common" varieties that are supplied in both of these time periods. In particular, we partition the set of firms from exporter i supplying importer j within sector g in periods $t-1$ and t (Ω^F_{jigt-1} and Ω^F_{jigt} respectively) into the subsets of "common firms" that continue to supply this market in both periods ($\Omega^F_{jigt,t-1}$), firms that enter in period t (I^{F+}_{jigt}) and firms that exit after period $t-1$ (I^{F-}_{jigt-1}). Similarly, we partition the set of products supplied by each of these firms in that sector into "common products" ($\Omega^U_{ft,t-1}$), entering products (I^{U+}_{ft}) and exiting products (I^{U-}_{ft-1}). A foreign exporting country enters an import market within a given sector when its first firm begins to supply that market and exits when its last firm ceases to supply that market. We can thus define analogous sets of foreign exporting countries $i \neq j$ for importer j and sector g: "common" ($\Omega^E_{jgt,t-1}$), entering (I^{E+}_{jgt}) and exiting (I^{E-}_{jgt-1}). We denote the number of elements in these common sets of firms, products and foreign exporters by $N^F_{jigt,t-1}$, $N^U_{ft,t-1}$ and $N^E_{jgt,t-1}$ respectively.

To incorporate entry and exit into the firm price index, we compute the shares of firm expenditure on common products in periods t and $t-1$ as follows:

$$\lambda^U_{ft} \equiv \frac{\sum_{u\in\Omega^U_{ft,t-1}} \left(P^U_{ut}/\varphi^U_{ut}\right)^{1-\sigma^U_g}}{\sum_{u\in\Omega^U_{ft}} \left(P^U_{ut}/\varphi^U_{ut}\right)^{1-\sigma^U_g}}, \qquad \lambda^U_{ft-1} \equiv \frac{\sum_{u\in\Omega^U_{ft,t-1}} \left(P^U_{ut-1}/\varphi^U_{ut-1}\right)^{1-\sigma^U_g}}{\sum_{u\in\Omega^U_{ft-1}} \left(P^U_{ut-1}/\varphi^U_{ut-1}\right)^{1-\sigma^U_g}}, \tag{19}$$

where recall that $\Omega^U_{ft,t-1}$ is the set of common products such that $\Omega^U_{ft,t-1} \subseteq \Omega^U_{ft}$ and $\Omega^U_{ft,t-1} \subseteq \Omega^U_{ft-1}$.

Using these common expenditure shares, the change in the log firm price index between periods $t-1$ and t ($\ln\left(P^F_{ft}/P^F_{ft-1}\right)$) can be exactly decomposed into four terms that are analogous to those for our levels decomposition in Eq. (18) above:

$$\ln\left(\frac{P^F_{ft}}{P^F_{ft-1}}\right) = \underbrace{\mathbb{E}^{U*}_{ft}\left[\ln\left(\frac{P^U_{ut}}{P^U_{ut-1}}\right)\right]}_{\text{(i) Average log prices}} - \underbrace{\mathbb{E}^{U*}_{ft}\left[\ln\left(\frac{\varphi^U_{ut}}{\varphi^U_{ut-1}}\right)\right]}_{\text{(ii) Average log appeal}} + \underbrace{\frac{1}{\sigma^U_g-1}\mathbb{E}^{U*}_{ft}\left[\ln\left(\frac{S^{U*}_{ut}}{S^{U*}_{ut-1}}\right)\right]}_{\text{(iii) Dispersion appeal-adjusted prices}} + \underbrace{\frac{1}{\sigma^U_g-1}\ln\left(\frac{\lambda^U_{ft}}{\lambda^U_{ft-1}}\right)}_{\text{(iv) Variety}}, \tag{20}$$

as shown in Section A.2.8 of the Online Appendix; $\mathbb{E}^{U*}_{ft}\left[\ln\left(P^U_{ut}/P^U_{ut-1}\right)\right] \equiv \frac{1}{N^U_{ft,t-1}}\sum_{u\in\Omega^U_{ft,t-1}} \ln\left(P^U_{ut}/P^U_{ut-1}\right)$; the superscript U^* indicates that the mean is taken across common products; and the subscripts f and t indicate that this mean varies across firms and over time; S^{U*}_{ut} is the share of an individual common product in expenditure on all common products, which takes the same form as the expression in Eq. (12), except that the summation in the denominator is over the set of common products ($\Omega^U_{ft,t-1}$). If entering varieties are either more numerous or have lower appeal-adjusted prices than exiting varieties, the common goods expenditure share at time t is lower than at time $t-1$, implying a fall in the price index ($\ln\left(\lambda^U_{ft}/\lambda^U_{ft-1}\right) < 0$).

We refer to the exact CES price index in Eq. (20) as the "unified price index" (UPI), because the time-varying appeal shifters for each product (φ^U_{ut}) ensure that it exactly rationalizes the micro data on prices and expenditure shares, while at the same time it permits exact aggregation to the macro level, thereby unifying micro and macro. This price index shares the same variety correction term $\left(\lambda^U_{ft}/\lambda^U_{ft-1}\right)^{1/\left(\sigma^U_g-1\right)}$ as Feenstra (1994). The key difference from Feenstra (1994) is the formulation of the price index for common goods, which we refer to as the "common-goods unified price index" (CG-UPI). Instead of using the Sato-Vartia price index for common goods, which assumes time-invariant appeal for each common good, we use the formulation of this price index for common goods from Redding and Weinstein (2020), which allows for changes in appeal for each common good over time.

2.9. Exporter price movements

Having inverted the model to recover the unobserved appeal parameters that rationalize the observed data, we now show how to aggregate to the exporter price index that summarizes the cost of sourcing goods across countries and sectors. Recursively applying our log linear representation of the CES price index in Eq. (18) for the exporter and firm price indexes, we obtain the following exact log-linear decomposition of the exporter price index, as shown in Section A.2.9 of the Online Appendix:

$$\begin{aligned}\ln \mathbb{P}^E_{jigt} = {} & \underbrace{\mathbb{E}^{FU}_{jigt}\left[\ln P^U_{ut}\right]}_{\text{(i) Average log prices}} - \underbrace{\left\{\mathbb{E}^F_{jigt}\left[\ln \varphi^F_{ft}\right] + \mathbb{E}^{FU}_{jigt}\left[\ln \varphi^U_{ut}\right]\right\}}_{\text{(ii) Average log appeal}} + \underbrace{\left\{\frac{1}{\sigma^U_g-1}\mathbb{E}^{FU}_{jigt}\left[\ln S^U_{ut} - \ln\frac{1}{N^U_{ft}}\right] + \frac{1}{\sigma^F_g-1}\mathbb{E}^F_{jigt}\left[\ln \mathbb{S}^{EF}_{ft} - \ln\frac{1}{N^F_{jigt}}\right]\right\}}_{\text{(iii) Dispersion appeal-adjusted prices}} \\ & - \underbrace{\left\{\frac{1}{\sigma^U_g-1}\mathbb{E}^F_{jigt}\left[\ln N^U_{ft}\right] + \frac{1}{\sigma^F_g-1}\ln N^F_{jigt}\right\}}_{\text{(iv) Variety}},\end{aligned} \tag{21}$$

where recall that j indexes the importer; i indexes the exporter; g indexes the sector; t indexes time; $\mathbb{S}_{ft}^{EF}$ is the share of a firm in imports from an individual exporting country and sector, as defined in Section A.2.9 of the Online Appendix; $\mathbb{E}_{jigt}^{FU}\left[\ln P_{ut}^{U}\right] \equiv \frac{1}{N_{jigt}^{F}} \sum_{f\in\Omega_{jigt}^{F}} \frac{1}{N_{ft}^{U}} \sum_{u\in\Omega_{ft}^{U}} \ln P_{ut}^{U}$ is a mean across firms and products within that exporting country and sector; and $\mathbb{E}_{jigt}^{F}\left[\ln P_{ft}^{F}\right] \equiv \frac{1}{N_{jigt}^{F}} \sum_{f\in\Omega_{jigt}^{F}} \ln P_{ft}^{F}$ is a mean across firms for that country and sector.

Similarly, partitioning varieties into those that are common, entering and exiting, and taking differences over time, we obtain an analogous exact log linear decomposition for changes in the exporter price index:

$$\Delta \ln \mathbb{P}_{jigt}^{E} = \underbrace{\mathbb{E}_{jigt}^{FU*}\left[\Delta \ln P_{ut}^{U}\right]}_{\text{(i) Average log prices}} - \underbrace{\left\{\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \varphi_{ft}^{F}\right] + \mathbb{E}_{jigt}^{FU*}\left[\Delta \ln \varphi_{ut}^{U}\right]\right\}}_{\text{(ii) Average log appeal}} + \underbrace{\left\{\frac{1}{\sigma_{g}^{U}-1}\mathbb{E}_{jigt}^{FU*}\left[\Delta \ln S_{ut}^{U*}\right] + \frac{1}{\sigma_{g}^{F}-1}\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \mathbb{S}_{ft}^{EF}\right]\right\}}_{\text{(iii) Dispersion appeal-adjusted prices}}$$
$$+ \underbrace{\left\{\frac{1}{\sigma_{g}^{U}-1}\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \lambda_{ft}^{U}\right] + \frac{1}{\sigma_{g}^{F}-1}\Delta \ln \lambda_{jigt}^{F}\right\}}_{\text{(iv) Variety}}, \tag{22}$$

as also shown in Section A.2.9 of the Online Appendix.

Eqs. (21) and (22) make explicit the three key features of our framework that allow exact aggregation from micro to macro. First, we can invert the model to recover the unobserved appeal parameters $\{\varphi_{ut}^{U}, \varphi_{ft}^{F}, \varphi_{gt}^{G}\}$ that rationalize the observed data. Second, for each tier of utility, the CES price index can be written as a log linear form of these appeal parameters and the observed data. Third, demand is nested, such that the price index for utility tier K depends on the price index and appeal parameters for utility tier $K-1$. Combining these three properties, and noting that the mean for tier K of the means from tier $K-1$ remains linear, we obtain our exact log linear decomposition of aggregate variables into the contributions of different mechanisms.

Each of the terms in these equations have an intuitive interpretation. The first term in Eq. (22) is the average log change in the price of common products sourced from exporting country i within sector g ($\mathbb{E}_{jigt}^{FU*}\left[\Delta \ln P_{ut}^{U}\right]$). This first component equals the log of a Jevons Index, which is a standard empirical measure of average prices, and is used to aggregate prices in the U.S. consumer price index.

The second term ($\mathbb{E}_{jigt}^{F*}\left[\ln \varphi_{ft}^{F}\right] + \mathbb{E}_{jigt}^{FU*}\left[\ln \varphi_{ut}^{U}\right]$) captures changes in appeal or quality upgrading for common products and firms and its presence reflects the fact that consumers care about appeal-adjusted prices rather than prices alone. Recall that our normalization in equation (A.2.4) implies that the average log change in common-product appeal within foreign firms is equal to zero: $\mathbb{E}_{jigt}^{FU*}\left[\Delta \ln \varphi_{ut}^{U}\right] = 0$. Similarly, our normalization in equation (A.2.7) implies that the average log change in firm appeal across *all* common foreign firms within a sector is equal to zero: $\mathbb{E}_{jgt}^{F*}\left[\Delta \ln \varphi_{ft}^{F}\right] = 0$. Nevertheless, the relative appeal of firms in different foreign countries within that sector can change, if appeal rises in some countries relative to others, in which case this second term is non-zero: $\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \varphi_{ft}^{F}\right] \neq \mathbb{E}_{jgt}^{F*}\left[\Delta \ln \varphi_{ft}^{F}\right] = 0$ for country $i \neq j$. Therefore, if one foreign exporter upgrades its appeal relative to another, this implies a fall in the cost of sourcing imports from that exporter relative to other foreign exporters.

The third term captures the dispersion of appeal-adjusted prices across common products and firms for a given exporter and sector. Other things equal, if the dispersion of these appeal-adjusted prices increases, this reduces the cost of sourcing goods from that exporter and sector ($\mathbb{E}_{jigt}^{FU*}\left[\Delta \ln S_{ut}^{U*}\right] < 0$ and $\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \mathbb{S}_{ft}^{EF}\right] < 0$). The reason is that this increased dispersion of appeal-adjusted prices enhances the ability of consumers to substitute away from varieties with high appeal-adjusted prices and towards those with low appeal-adjusted prices.

The fourth term in Eq. (22) ($\frac{1}{\sigma_{g}^{U}-1}\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \lambda_{ft}^{U}\right] + \frac{1}{\sigma_{g}^{F}-1}\Delta \ln \lambda_{jigt}^{F}$) captures the effect of product turnover and firm entry and exit on the cost of sourcing imports from a given exporter and sector. If entering firms and products are more numerous or desirable than exiting firms and products, this again reduces the cost of sourcing goods from that exporter and sector ($\mathbb{E}_{jigt}^{F*}\left[\Delta \ln \lambda_{ft}^{U}\right] < 0$ and $\Delta \ln \lambda_{jigt}^{F} < 0$).

2.10. Patterns of trade across sectors and countries

Thus far, we have been focused on measuring the price indexes that determine the costs of sourcing goods from a given exporter and sector. The move from price indexes to trade patterns, however, is straightforward, because these patterns of trade are determined by relative price indexes. We can therefore translate our results for exporter price indexes into the determinants of patterns of trade across countries and sectors.

2.10.1. Revealed comparative advantage

We begin by defining a measure of revealed comparative advantage (RCA) that holds in nested CES demand systems and can be used to decompose the variation in RCA into the contribution of different theoretical mechanisms. We start with importer j's expenditure on foreign exporter $i \neq j$ as a share of its expenditure on all foreign exporters within sector g at time t:

$$\mathbb{S}_{jigt}^{E} = \frac{\sum_{f\in\Omega_{jigt}^{F}}\left(P_{ft}^{F}/\varphi_{ft}^{F}\right)^{1-\sigma_{g}^{F}}}{\sum_{h\in\Omega_{jgt}^{E}}\sum_{f\in\Omega_{jhgt}^{F}}\left(P_{ft}^{F}/\varphi_{ft}^{F}\right)^{1-\sigma_{g}^{F}}} = \frac{\left(\mathbb{P}_{jigt}^{E}\right)^{1-\sigma_{g}^{F}}}{\left(\mathbb{P}_{jgt}^{G}\right)^{1-\sigma_{g}^{F}}}, \qquad i \neq j. \tag{23}$$

where the single superscript E is a mnemonic for exporter and indicates that this is the expenditure share for a foreign exporting country $i \neq j$; the numerator in Eq. (23) captures importer j's price index for exporting country i in sector g at time t ($\mathbb{P}^E_{jigt}$); and the denominator in Eq. (23) features importer j's overall import price index in sector g at time t ($\mathbb{P}^G_{jgt}$).

Using the definition of this exporter expenditure share (23), we measure RCA in sector g for import market j, by first taking the value of country i's exports relative to the geometric mean across countries for that sector ($\mathbb{X}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{X}^E_{jigt}\right]$), and then dividing by country i's geometric mean of this ratio across tradable sectors ($\mathbb{M}^T_{jit}\left[\mathbb{X}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{X}^E_{jigt}\right]\right]$):

$$RCA_{jigt} \equiv \frac{\mathbb{X}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{X}^E_{jigt}\right]}{\mathbb{M}^T_{jit}\left[\mathbb{X}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{X}^E_{jigt}\right]\right]} = \frac{\mathbb{S}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{S}^E_{jigt}\right]}{\mathbb{M}^T_{jit}\left[\mathbb{S}^E_{jigt}/\mathbb{M}^E_{jgt}\left[\mathbb{S}^E_{jigt}\right]\right]}, \tag{24}$$

where we use $\mathbb{X}^E_{jigt}$ to denote the value of bilateral exports from country i to importer $j \neq i$ within sector g at time t; $\mathbb{M}^E_{jgt}\left[\mathbb{X}^E_{jigt}\right] = \left(\prod_{h\in\Omega^E_{jgt}} \mathbb{X}^E_{jhgt}\right)^{1/N^E_{jgt}}$ is the geometric mean of these exports across all foreign exporters for that importer and sector; $\mathbb{M}^T_{jit}\left[\mathbb{X}^E_{jigt}\right] = \left(\prod_{k\in\Omega^T_{jit}} \mathbb{X}^E_{jikt}\right)^{1/N^T_{jit}}$ is the geometric mean of these exports across tradable sectors for that importer and foreign exporter; and $\mathbb{S}^E_{jigt} = \mathbb{X}^E_{jigt}/\sum_{h\in\Omega^E_{jgt}} \mathbb{X}^E_{jhgt} = \mathbb{X}^E_{jigt}/\mathbb{X}^G_{jgt}$ is the share of foreign exporter $i \neq j$ in country j's imports from all foreign countries within sector g at time t.

From Eq. (24), an exporter has a *revealed comparative advantage* in a sector within a given import market (a value of RCA_{jigt} greater than one) if its exports relative to the average exporter in that sector are larger than for its average sector. This RCA measure is similar to those in Costinot et al. (2012) and Levchenko and Zhang (2016). However, instead of choosing an individual sector and country as the base for the double-differencing, we first difference relative to a hypothetical country within a sector (equal to the geometric mean country for that sector), and then second difference relative to a hypothetical sector (equal to the geometric mean across sectors).[8] Additionally, we derive our RCA measure solely from our nested CES preference structure, without making supply-side assumptions.

As we now show, these differences enable us to quantify the role of different economic mechanisms in understanding patterns of trade across countries and sectors. From Eqs. (23) and (24), RCA captures the relative cost to an importer of sourcing goods across countries and sectors, as determined by relative price indexes and the elasticity of substitution ($\left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g}$):

$$RCA_{jigt} = \frac{\left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g}/\mathbb{M}^E_{jgt}\left[\left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g}\right]}{\mathbb{M}^T_{jit}\left[\left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g}/\mathbb{M}^E_{jgt}\left[\left(\mathbb{P}^E_{jigt}\right)^{1-\sigma^F_g}\right]\right]}. \tag{25}$$

Taking logarithms in Eq. (25), and using Eq. (21) to substitute for the log exporter price index ($\ln \mathbb{P}^E_{jigt}$), we can decompose differences in log RCA across countries and sectors into the contributions of average log prices ($\ln\left(RCA^P_{jigt}\right)$), average log appeal ($\ln\left(RCA^\varphi_{jigt}\right)$), the dispersion of appeal-adjusted prices ($\ln\left(RCA^S_{jigt}\right)$), and variety ($\ln\left(RCA^N_{jigt}\right)$):

$$\ln\left(RCA_{jigt}\right) = \underbrace{\ln\left(RCA^P_{jigt}\right)}_{\text{(i) Average log prices}} + \underbrace{\ln\left(RCA^\varphi_{jigt}\right)}_{\text{(ii) Average log appeal}} + \underbrace{\ln\left(RCA^S_{jigt}\right)}_{\text{(iii) Dispersion appeal-adjusted prices}} + \underbrace{\ln\left(RCA^N_{jigt}\right)}_{\text{(iv) Variety}}, \tag{26}$$

where $\ln\left(RCA^P_{jigt}\right)$ is defined as:

$$\ln\left(RCA^P_{jigt}\right) \equiv \left\{\begin{array}{l} \left(1-\sigma^F_g\right)\left[\mathbb{E}^{FU}_{jigt}\left[\ln P^U_{ut}\right] - \frac{1}{N^E_{jgt}}\sum_{h\in\Omega^E_{jgt}} \mathbb{E}^{FU}_{jhgt}\left[\ln P^U_{ut}\right]\right] \\ -\frac{1}{N^T_{jit}}\sum_{k\in\Omega^T_{jit}}\left(1-\sigma^F_k\right)\left[\mathbb{E}^{FU}_{jikt}\left[\ln P^U_{ut}\right] - \frac{1}{N^E_{jkt}}\sum_{h\in\Omega^E_{jkt}} \mathbb{E}^{FU}_{jhkt}\left[\ln P^U_{ut}\right]\right] \end{array}\right\}$$

and each of the other terms is defined analogously, as shown in Section A.2.10.1 of the Online Appendix.

The four terms in Eq. (26) capture the four mechanisms determining patterns of trade across countries and industries in the leading theories of international trade discussed above. The first term captures variation in prices, which is the mechanism through which technology and endowments are typically interpreted as affecting patterns of trade in neoclassical theories of international trade. The second term reflects differences in product appeal, as considered in recent research on product quality in international trade, including Khandelwal (2010), Hallak and Schott (2011), and Feenstra and Romalis (2014). The third term encapsulates heterogeneity in prices and appeal across and within firms, as stressed in theories of heterogeneous firms following Melitz (2003),

[8] Our measure also relates closely to Balassa (1965)'s original measure of RCA, which divides a country's exports in a sector by the total exports of all countries in that sector, and then divides this ratio by the country's share of overall exports across all sectors. Instead, we divide a country's exports in a sector by the geometric mean exports in that sector across countries, and then divide this ratio by its geometric mean across sectors.

including Bernard et al. (2007b, 2011). The fourth term summarizes the contribution of the number of firm-product varieties, as highlighted by theories of product differentiation and increasing returns to scale following Krugman (1980) and Helpman and Krugman (1985).

Each term is a double difference in logs, in which we first difference a variable for an exporter and sector relative to the mean across exporters for that sector (as in the numerator of RCA), before then second differencing the variable across sectors (as in the denominator of RCA). For example, to compute the average log price term ($\ln\left(RCA^{P}_{jigt}\right)$), we proceed as follows. In a first step, we compute average log product prices for an exporter and sector in an import market. In a second step, we subtract from these average log product prices their mean across all exporters for that sector and import market. In a third step, we difference these scaled average log product prices from their mean across all sectors for that exporter and import market. Other things equal, an exporter has a RCA in a sector if its log product prices relative to the average exporter in that sector are low compared to their values in the average sector.

A key implication of Eq. (26) is that comparative advantage depends on demand-side assumptions when goods are differentiated ($\sigma^{U}_{g} < \infty$, $\sigma^{F}_{g} < \infty$, $\varphi^{U}_{ut} \neq \varphi^{U}_{\ell t}$ for $u \neq \ell$, and $\varphi^{F}_{ft} \neq \varphi^{F}_{mt}$ for $f \neq m$), which is consistent with the idea in the industrial organization literature that productivity depends on demand-side assumptions when goods are differentiated.[9] The reason is that comparative advantage depends on relative price indexes, which cannot be inferred from relative prices alone if goods are differentiated. In such a setting, average appeal, the number of products and firms, and the dispersion of appeal-adjusted prices across these products and firms (as captured by the dispersion of expenditure shares) are also important determinants of relative price indexes.

Similarly, partitioning varieties into those that are common, entering and exiting, and taking differences over time, we can decompose changes in RCA across countries and sectors into four analogous terms:

$$\Delta \ln\left(RCA^{*}_{jigt}\right) = \underbrace{\Delta \ln\left(RCA^{P*}_{jigt}\right)}_{\text{(i) Average log prices}} + \underbrace{\Delta \ln\left(RCA^{\varphi*}_{jigt}\right)}_{\text{(ii) Average log appeal}} + \underbrace{\Delta \ln\left(RCA^{S*}_{jigt}\right)}_{\text{(iii) Dispersion appeal-adjusted prices}} + \underbrace{\Delta \ln\left(RCA^{\lambda}_{jigt}\right)}_{\text{(iv) Variety}}, \tag{27}$$

where each of these terms again relates to the leading theories of international trade discussed above, and these four terms are defined in full in Subsection A.2.10.1 of the Online Appendix.

The interpretation of these four terms is similar to that for our decomposition of exporter price indexes above. Other things equal, an exporter's RCA in a sector rises if its prices fall faster than its competitors in that sector than in other sectors. The second term incorporates the effects of average log appeal. All else constant, RCA increases in a sector if an exporter's appeal rises more rapidly than its competitors in that sector than in other sectors. The third term summarizes the impact of the dispersion of appeal-adjusted prices across varieties. Other things equal, RCA rises for an exporter in a sector if the dispersion of appeal-adjusted prices increases relative to its competitors in that sector by more than in other sectors. As its appeal-adjusted prices become more dispersed, this enables consumers to more easily substitute from the exporter's less attractive varieties to its more attractive varieties, which increases the demand for its goods. Finally, the fourth term summarizes the contribution of entry/exit. All else constant, if entering varieties are more numerous or have lower appeal-adjusted prices than exiting varieties, this increases the value of trade. Therefore, an exporter's RCA in a sector increases if it has a larger contribution from entry and exit relative to its competitors in that sector than in other sectors.

2.10.2. Aggregate trade

We now aggregate further to obtain an exact log linear decomposition of exporting countries' shares of total imports. We use this decomposition to examine the reasons for the large-scale changes in countries' import shares over our sample period, which includes the dramatic rise in Chinese import penetration. At first sight, our ability to obtain log linear decompositions of both sectoral and aggregate trade is somewhat surprising, because aggregate trade is the sum of sectoral trade (rather than the sum of log sectoral trade). We show below that we are able to do so because the structure of CES demand yields a closed-form solution for an exact Jensen's Inequality correction term that controls for the difference between the log of the sum and the sum of the logs.[10]

Partitioning varieties into common, entering and exiting varieties, we show in Section A.2.10.2 of the Online Appendix that the log change in the share of foreign exporter i in importer j's total expenditure on all foreign exporters can be exactly decomposed as follows:

$$\Delta \ln \mathbb{S}^{E}_{jit} = \underbrace{-\left\{\mathbb{E}^{TFU*}_{jit}\left[\left(\sigma^{F}_{g}-1\right)\Delta \ln P^{U}_{ut}\right] - \mathbb{E}^{TEFU*}_{jt}\left[\left(\sigma^{F}_{g}-1\right)\Delta \ln P^{U}_{ut}\right]\right\}}_{\text{(i) Average log prices}}$$
$$+ \underbrace{\left\{\mathbb{E}^{TFU*}_{jit}\left[\left(\sigma^{F}_{g}-1\right)\Delta \ln \varphi^{U}_{ut}\right] - \mathbb{E}^{TEFU*}_{jt}\left[\left(\sigma^{F}_{g}-1\right)\Delta \ln \varphi^{U}_{ut}\right]\right\}}_{\text{(ii) Average log product appeal}}$$

[9] For a discussion of the centrality of demand-side assumptions to productivity measurement when goods are imperfect substitutes, see for example Foster et al. (2008) and De Loecker and Goldberg (2014).

[10] This property that both sectoral and aggregate trade have log linear representations under nested CES preferences provides microfoundations for empirical findings that the gravity equation provides a good approximation to both sectoral and aggregate trade, as examined in Redding and Weinstein (2019).

$$
\begin{aligned}
&+ \underbrace{\left\{ \mathbb{E}_{jit}^{TF*}\left[\left(\sigma_g^F-1\right)\Delta\ln\varphi_{ft}^F\right]-\mathbb{E}_{jt}^{TEF*}\left[\left(\sigma_g^F-1\right)\Delta\ln\varphi_{ft}^F\right]\right\}}_{\text{(iii) Average log firm appeal}} \\
&- \underbrace{\left\{ \mathbb{E}_{jit}^{TFU*}\left[\frac{\sigma_g^F-1}{\sigma_g^U-1}\Delta\ln S_{ut}^{U*}\right]-\mathbb{E}_{jt}^{TEFU*}\left[\frac{\sigma_g^F-1}{\sigma_g^U-1}\Delta\ln S_{ut}^{U*}\right]\right\}}_{\text{(iv) Dispersion appeal-adjusted product prices}} - \underbrace{\left\{ \mathbb{E}_{jit}^{TF*}\left[\Delta\ln\mathbb{S}_{ft}^{EF*}\right]-\mathbb{E}_{jt}^{TEF*}\left[\Delta\ln\mathbb{S}_{ft}^{EF*}\right]\right\}}_{\text{(v) Dispersion appeal-adjusted firm prices}} \\
&- \underbrace{\left\{ \mathbb{E}_{jit}^{TF*}\left[\frac{\sigma_g^F-1}{\sigma_g^U-1}\Delta\ln\lambda_{ft}^U\right]-\mathbb{E}_{jt}^{TEF*}\left[\frac{\sigma_g^F-1}{\sigma_g^U-1}\Delta\ln\lambda_{ft}^U\right]\right\}}_{\text{(vi) Product Variety}} - \underbrace{\left\{ \mathbb{E}_{jit}^{T}\left[\Delta\ln\lambda_{jigt}^F\right]-\mathbb{E}_{jt}^{TE*}\left[\Delta\ln\lambda_{jigt}^F\right]\right\}}_{\text{(vii) Firm Variety}} \\
&- \underbrace{\Delta\ln\left(\lambda_{jit}^E/\lambda_{jt}^T\right)}_{\text{(viii) Country-Sector Variety}} \\
&+ \underbrace{\Delta\ln\mathbb{K}_{jit}^T}_{\text{(ix) Country-sector Scale}} + \underbrace{\Delta\ln\mathbb{J}_{jit}^T}_{\text{(x) Country-sector Concentration}},
\end{aligned} \tag{28}
$$

where $\Delta\ln\mathbb{K}_{jit}^T$ and $\Delta\ln\mathbb{J}_{jit}^T$ are defined as

$$
\Delta\ln\mathbb{K}_{jit}^T \equiv \Delta\ln\left[\frac{\mathbb{M}_{jit}^{T*}\left[\mathbb{X}_{jgt}^G\right]\left(\mathbb{M}_{jit}^{T*}\left[\left(\mathbb{P}_{jgt}^G\right)^{\sigma_g^F-1}\right]\right)}{\mathbb{M}_{jt}^{TE*}\left[\mathbb{X}_{jgt}^G\right]\left(\mathbb{M}_{jt}^{TE*}\left[\left(\mathbb{P}_{jgt}^G\right)^{\sigma_g^F-1}\right]\right)}\right],
$$

$$
\Delta\ln\mathbb{J}_{jit}^T \equiv \Delta\ln\left[\frac{\mathbb{M}_{jt}^{TE*}\left[\mathbb{Y}_{jigt}^{E*}\right]}{\mathbb{M}_{jit}^{T*}\left[\mathbb{Z}_{jigt}^{E*}\right]}\right],
$$

and $\mathbb{E}_{jt}^{TEFU*}[\cdot]$, $\mathbb{E}_{jit}^{TFU*}[\cdot]$, $\mathbb{E}_{jit}^{TF*}[\cdot]$, $\mathbb{E}_{jt}^{TEF*}[\cdot]$, $\mathbb{E}_{jt}^{TE*}[\cdot]$ and $\mathbb{E}_{jit}^{T}[\cdot]$ are means across sectors, exporters, firms and products, as defined in Section A.2.10.2 of the Online Appendix.

Again the different terms in Eq. (28) connect directly to the leading theories of international trade discussed above. The first term captures variation in prices, as determined by endowments and technology in neoclassical theories of international trade. The second and third terms reflect differences in product appeal, including product quality. The fourth and fifth terms encapsulate heterogeneity in prices and appeal across and within firms, as stressed in theories of heterogeneous firms. The sixth, seventh and eighth terms summarize the contribution of the number of varieties, as highlighted by theories of product differentiation and increasing returns to scale. The ninth and tenth terms aggregate across industries and depend on the scale and concentration of sales across industries.

From the first term (i), an exporter's import share increases if the average prices of its products fall more rapidly than those of other exporters. In the second term (ii), our choice of units for product appeal in equation (A.2.4) implies that the average log change in appeal across common products within firms is equal to zero ($\mathbb{E}_{ft}^{U*}\left[\Delta\ln\varphi_{ut}^U\right]$), which implies that this second term is equal to zero. From the third term (iii), an exporter's import share also increases if the average appeal of its firms rises more rapidly than that of firms from other exporters within each sector (recall that our choice of units for firm appeal only implies that its average log change equals zero across *all* foreign firms within each sector).

The fourth and fifth terms ((iv) and (v)) capture the dispersion of appeal-adjusted prices across common products and firms. An exporter's import share increases if appeal-adjusted prices become more dispersed across its products and firms compared to other foreign exporters. The sixth through eighth terms ((vi)-(viii)) capture the contribution of entry/exit to changes in country import shares. An exporter's import share increases if its entering products, firms and sectors are more numerous and/or have lower appeal-adjusted prices compared to its exiting varieties than those for other foreign exporters.

The last two terms capture sectoral compositional effects. From the penultimate term (ix), an exporter's import share increases if its exports become more concentrated in sectors that account for large expenditure shares relative to the exports of other foreign countries. The final term (x) captures the concentration of imports across sectors for an individual exporter relative to their concentration across sectors for all foreign countries. This final term is the exact Jensen's Inequality correction term discussed above.

2.11. Aggregate prices

In addition to understanding aggregate trade patterns, researchers are often interested in understanding movements in the aggregate cost of living, since this is an important determinant of real income and welfare. In Section A.2.11 of the Online Appendix, we show that the change in the aggregate price index in Eq. (4) can be exactly decomposed into the following five terms:

$$
\underbrace{\Delta\ln P_{jt}}_{\substack{\text{Aggregate}\\ \text{Price Index}}} = \underbrace{\frac{1}{\sigma^G-1}\Delta\ln\mu_{jt}^T}_{\substack{\text{Non-Tradable}\\ \text{Competitiveness}}} + \underbrace{\mathbb{E}_{jt}^T\left[\frac{1}{\sigma_g^F-1}\Delta\ln\mu_{jgt}^G\right]}_{\substack{\text{Domestic}\\ \text{Competitiveness}}} + \underbrace{\mathbb{E}_{jt}^T\left[\Delta\ln\varphi_{jgt}^G\right]}_{\substack{\text{Average}\\ \text{Appeal}}} + \underbrace{\mathbb{E}_{jt}^T\left[\frac{1}{\sigma^G-1}\Delta\ln\mathbb{S}_{jgt}^T\right]}_{\substack{\text{Dispersion appeal-}\\ \text{adjusted prices across sectors}}} + \underbrace{\mathbb{E}_{jt}^T\left[\Delta\ln\mathbb{P}_{jgt}^G\right]}_{\substack{\text{Aggregate Import}\\ \text{Price Indexes}}}, \tag{29}
$$

where $\mathbb{S}^T_{jgt}$ is the share of an individual tradable sector in expenditure on all tradable sectors. Recall that the set of tradable sectors is constant over time and hence there are no terms for the entry and exit of sectors in Eq. (29).

The first three terms capture shifts in aggregate prices that can be inferred from changes in market shares or demand. The first term ($\frac{1}{\sigma^G-1}\Delta\ln\mu^T_{jt}$) captures the relative attractiveness of varieties in the tradable and non-tradable sectors. Other things equal, a fall in the share of expenditure on tradable sectors ($\Delta\ln\mu^I_{jt}<0$) implies that varieties in non-tradable sectors have become relatively more attractive under elastic demand, which reduces the cost of living. The second term ($\mathbb{E}^T_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\mu^G_{jgt}\right]$) captures the relative attractiveness of domestic varieties within sectors. Other things equal, a fall in the average share of expenditure on foreign varieties within sectors ($\mathbb{E}^T_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\mu^G_{jgt}\right]<0$) implies that domestic varieties have become relatively more attractive within sectors under elastic demand, which again reduces the cost of living. The third term ($\mathbb{E}^T_{jt}\left[\Delta\ln\varphi^G_{jgt}\right]$) captures changes in the average appeal for tradable sectors, where the superscript T on the expectation indicates that this mean is taken across the subset of tradable sectors ($\Omega^T\subseteq\Omega^G$). Given our choice of units in which to measure sector appeal, this third term is equal to zero ($\mathbb{E}^T_{jt}\left[\Delta\ln\varphi^G_{jgt}\right]=0$). The fourth term ($\mathbb{E}^T_{jt}\left[\frac{1}{\sigma^G-1}\Delta\ln\mathbb{S}^G_{jgt}\right]$) captures changes in the dispersion of appeal-adjusted prices across tradable sectors. Intuitively, when sectors are substitutes ($\sigma^G>1$), an increase in the dispersion of appeal-adjusted prices across sectors reduces the cost of living, because it enhances the ability of consumers to substitute from less to more desirable sectors. The fifth and final term ($\mathbb{E}^T_{jt}\left[\Delta\ln\mathbb{P}^G_{jgt}\right]$) captures changes in aggregate import price indexes across all tradable sectors. Other things equal, a fall in these aggregate import price indexes ($\mathbb{E}^T_{jt}\left[\Delta\ln\mathbb{P}^G_{jgt}\right]<0$) reduces the cost of living. We now show that this fifth term can be further decomposed.

Partitioning goods into common, entering and exiting varieties, Section A.2.11 of the Online Appendix shows that the change in aggregate import price indexes can be exactly decomposed as follows:

$$\begin{aligned}\underbrace{\mathbb{E}^T_{jt}\left[\Delta\ln\mathbb{P}^G_{jgt}\right]}_{\substack{\text{Aggregate Import}\\\text{Price Indexes}}}=&\underbrace{\mathbb{E}^{TEFU*}_{jt}\left[\Delta\ln P^U_{ut}\right]}_{\text{Average log prices}}-\underbrace{\mathbb{E}^{TEF*}_{jt}\left[\Delta\ln\varphi^F_{ft}\right]}_{\substack{\text{Average log}\\\text{firm appeal}}}-\underbrace{\mathbb{E}^{TEFU*}_{jt}\left[\Delta\ln\varphi^U_{ut}\right]}_{\substack{\text{Average log}\\\text{product appeal}}}\\&\underbrace{\mathbb{E}^{TE*}_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\mathbb{S}^E_{jigt}\right]}_{\substack{\text{Dispersion country-sector}\\\text{appeal-adjusted prices}}}+\underbrace{\mathbb{E}^{TEF*}_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\mathbb{S}^{EF}_{ft}\right]}_{\substack{\text{Dispersion firm}\\\text{appeal-adjusted prices}}}+\underbrace{\mathbb{E}^{TEFU*}_{jt}\left[\frac{1}{\sigma^U_g-1}\Delta\ln S^U_{ut}\right]}_{\substack{\text{Dispersion product}\\\text{appeal-adjusted prices}}}\\&+\underbrace{\mathbb{E}^{T*}_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\lambda^E_{jgt}\right]}_{\substack{\text{Country - Sector}\\\text{Variety}}}+\underbrace{\mathbb{E}^{TE*}_{jt}\left[\frac{1}{\sigma^F_g-1}\Delta\ln\lambda^F_{jigt}\right]}_{\substack{\text{Firm}\\\text{Variety}}}+\underbrace{\mathbb{E}^{TEF*}_{jt}\left[\frac{1}{\sigma^U_g-1}\Delta\ln\lambda^U_{ft}\right]}_{\substack{\text{Product}\\\text{Variety}}},\end{aligned}\tag{30}$$

where again these terms relate to leading theories of international trade, which highlight either (i) price as the mechanism through which technology and endowments affect trade patterns; (ii) product appeal, including product quality (second and third terms); (iii) heterogeneity across and within producers (fourth, fifth and sixth terms); or (iv) product variety (seventh, eighth and ninth terms).

The interpretation of each of these components in Eq. (30) is analogous to the interpretation of the corresponding components of countries aggregate import shares in Eq. (28). Aggregate import price indexes fall as average product prices decline, as average firm and product appeal increase, as the dispersion of appeal-adjusted prices across surviving countries, firms and products increases, and if entering countries, firms and products are more numerous or more desirable than those that exit.

3. Structural estimation

In order to take our model to data, we need estimates of the elasticities of substitution $\{\sigma^U_g,\sigma^F_g,\sigma^G\}$. In our baseline specification, we estimate these elasticities of substitution using an extension of the reverse-weighting (RW) estimator of Redding and Weinstein (2023), as developed in Section A.3 of the Online Appendix. We also report robustness checks in Section A.3 of the Online Appendix, in which we compare our RW estimates of the elasticities of substitution to alternative estimates, and in which we examine the sensitivity of our results to alternative values of these elasticities of substitution using a grid search.

We extend the RW estimator to a nested demand system and show that the estimation problem is recursive. In a first step, we estimate the elasticity of substitution across products (σ^U_g) for each sector g. In a second step, we estimate the elasticity of substitution across firms (σ^F_g) for each sector g. In a third step, we estimate the elasticity of substitution across sectors (σ^G).

In this section, we illustrate the RW estimator for the product tier of utility, and report the full details of the nested estimation and the moment equation in Section A.3 of the Online Appendix. The RW estimator is based on three equivalent expressions for the change in the CES unit expenditure function: one from the demand system, a second from taking the forward difference of the unit expenditure function, and a third from taking the backward difference of the unit expenditure function. Together these three expressions imply the following two equalities

$$\Theta^{U+}_{ft,t-1}\left[\sum_{u\in\Omega^U_{ft,t-1}}S^{U*}_{ut-1}\left(\frac{P^U_{ut}}{P^U_{ut-1}}\right)^{1-\sigma^U_g}\right]^{\frac{1}{1-\sigma^U_g}}=\mathbb{M}^{U*}_{ft}\left[\frac{P^U_{ut}}{P^U_{ut-1}}\right]\left(\mathbb{M}^{U*}_{ft}\left[\frac{S^{U*}_{ut}}{S^{U*}_{ut-1}}\right]\right)^{\frac{1}{\sigma^U_g-1}},\tag{31}$$

$$\Theta_{ft,t-1}^{U-}\left[\sum_{u\in\Omega_{ft,t-1}^{U}} S_{ut}^{U*}\left(\frac{P_{ut}^{U}}{P_{ut-1}^{U}}\right)^{-\left(1-\sigma_g^U\right)}\right]^{-\frac{1}{1-\sigma_g^U}} = \mathbb{M}_{ft}^{U*}\left[\frac{P_{ut}^{U}}{P_{ut-1}^{U}}\right]\left(\mathbb{M}_{ft}^{U*}\left[\frac{S_{ut}^{U*}}{S_{ut-1}^{U*}}\right]\right)^{\frac{1}{\sigma_g^U-1}}, \tag{32}$$

where the variety correction terms ($\left(\lambda_{ft}^{U}/\lambda_{ft-1}^{U}\right)^{\frac{1}{\sigma_g^U-1}}$) have cancelled because they are common to all three expressions; $\Theta_{ft,t-1}^{U+}$ and $\Theta_{ft,t-1}^{U-}$ are forward and backward aggregate demand shifters respectively, which summarize the effect of changes in the relative appeal for individual products on the unit expenditure function (as defined in Section A.3 of the Online Appendix); finally the equalities in Eqs. (31) and (32) are robust to introducing a Hicks-neutral shifter of appeal across all products within each firm, which would cancel from both sides of the equation (like the variety correction term).

The RW estimator uses Eqs. (31) and (32) to estimate the elasticity of substitution across products (σ_g^U) under the assumption that the shocks to relative appeal cancel out across products:

$$\Theta_{ft,t-1}^{U+} = \left(\Theta_{ft,t-1}^{U-}\right)^{-1} = 1. \tag{33}$$

This assumption is necessarily satisfied as demand shocks become small ($\varphi_{ut}^{U}/\varphi_{ut-1}^{U} \to 1$ for all u). More generally, this assumption is satisfied up to a first-order approximation, as shown in Redding and Weinstein (2023). Therefore, the RW estimator can be interpreted as providing a first-order approximation to the data. In practice, we find that the RW estimated elasticities are similar to those estimated using other methods, such as the generalization of the Feenstra (1994) estimator used in Hottman et al. (2016). More generally, an advantage of CES preferences is that the elasticity of substitution between goods is controlled by a single parameter, which makes it easy to demonstrate the robustness of results to alternative values of this parameter using a grid search.

4. Data description

To undertake our empirical analysis of the determinants of trade patterns and aggregate prices, we use international trade transactions data that are readily available from customs authorities. In this section, we briefly discuss the U.S. trade transactions data that we use in this paper, and report further details in Section A.4.1 of the Online Appendix. In Section A.4.2 of the Online Appendix, we discuss the Chilean trade transactions data that we use in robustness tests in the Online Appendix.

For each U.S. import customs shipment, we observe the cost inclusive of freight value of the shipment in U.S. dollars (market exchange rates), the quantity shipped, the date of the transaction, the product classification (according to 10-digit Harmonized System (HS) codes), the country of origin, and a partner identifier containing information about the foreign exporting firm.[11] We concord the HS-digit 10-digit products to 4-digit sectors in the North American Industry Classification System (NAICS). We are thus able to construct a dataset for a single importer j (the U.S.) with many exporters i (countries of origin), sectors g (4-digit NAICs codes), firms f (foreign firm identifiers within exporters within sectors), and products u (10-digit HS codes within foreign firm identifiers, within exporters and within sectors) and time t (year). We standardize the units in which quantities are reported (e.g. we convert dozens to counts and grams to kilograms). We also drop any observations for which countries of origin or foreign firm identifiers are missing. Finally, we collapse the import shipments data to the annual level by exporting firm and product, weighting by trade value, which yields a dataset on U.S. imports by source country (exporter), foreign firm, product and year from 1997–2011. In our final year of 2011, we have over 3.7 million observations by exporter-firm-product.

Our measure of prices is the export unit value of an exporting firm within a 10-digit HS category. While these data necessarily involve some aggregation across different varieties of products supplied by the same exporting firm within an observed product category, Section A.7 of the Online Appendix shows that our framework allows for unobserved differences in composition within observed product categories. In this case, the product appeal shifter (φ_{ut}^{U}) that we recover from inverting the demand system captures both product appeal and the unobserved differences in composition. Moreover, 10-digit HS categories are relatively narrowly defined, and the coverage of sectors is much wider than in datasets that directly survey prices. As a result, many authors—including those working for statistical agencies—advocate for greater use of unit value data in the construction of import price indexes.[12] Furthermore, existing research comparing aggregate import price indexes constructed using unit values and directly surveyed prices finds only small differences between them, as reported using U.S. data in Amiti and Davis (2009). Similarly, in our data we find that the correlation between a Cobb–Douglas price index (using lagged import shares as weights) and the BLS import price index is 0.93, which suggests that unit value indexes capture much of the variation of import indexes based on price quotes.

In Section A.5.6 of the Online Appendix, we show that our U.S. trade transactions data exhibit the same properties as found by a number of existing studies in the empirical trade literature.[13] In particular, two key features of the observed data are the high concentration of trade across countries and the dramatic increase in Chinese import penetration. As shown in Figure A.5.5 of that section of the Online Appendix, the top 20 import source countries account for around 80 percent of U.S. imports in each year; China's import share more than doubles from 7 to 18 percent from 1997–2011; in contrast, Japan's import share more than halves from 14 to 6 percent over this same period.

[11] See Kamal et al. (2015) for further discussion of the U.S. trade transactions data and comparisons of these partner identifiers using import data for the U.S. and export data from foreign countries. In robustness checks, we show that we continue to find that the variety and average appeal terms dominate using Chilean trade transactions data that report foreign brands.

[12] For instance, Nakamura et al. (2015) argue for the superiority of indexes based on disaggregated unit value data on theoretical grounds and "recommend alternatives to conventional price indexes that make use of unit values".

[13] For example, see Bernard et al. (2009b) and Bernard et al. (2009a) for the U.S.; Mayer et al. (2014) for France; and Manova and Zhang (2012) for China.

Table 1
Estimated elasticities of substitution, within firms (σ_g^U), across firms (σ_g^F) and across sectors (σ^G) (U.S. Data).

Percentile	Elasticity across products (σ_g^U)	Elasticity across firms (σ_g^F)	Elasticity across sectors (σ^G)	Product-firm difference ($\sigma_g^U - \sigma_g^F$)	Firm-sector difference ($\sigma_g^F - \sigma^G$)
Min	5.14	1.97	1.36	1.51	0.60
5th	5.42	2.06	1.36	2.42	0.69
25th	5.85	2.36	1.36	3.13	1.00
50th	6.29	2.66	1.36	3.48	1.30
75th	6.99	3.41	1.36	3.94	2.04
95th	8.36	4.83	1.36	4.77	3.47
Max	10.59	7.66	1.36	5.51	6.30

Note: Estimated elasticities of substitution from the reverse-weighting estimator discussed in Section 3 and in Section A.3 of the Online Appendix. Sectors are 4-digit North American Industrial Classification (NAICS) codes; firms are foreign exporting firms within each foreign country within each sector; and products are 10-digit Harmonized System (HS) codes within foreign exporting firms within sectors.

5. Empirical results

We present our results in several stages. We begin in Section 5.1 by reporting our estimates of the elasticities of substitution (σ_g^U, σ_g^F, σ^G), which we use to invert the model and recover the values of product, firm and sector appeal (φ_{ut}^U, φ_{ft}^F, φ_{jgt}^G). In Section 5.2, we use these estimates to compute the exporter price indexes that determine the cost of sourcing goods across countries and sectors. In Section 5.3, we report our main results for comparative advantage, aggregate trade and aggregate prices. In Section 5.4, we compare the results of our framework with special cases that impose additional theoretical restrictions. In Section A.6 of the Online Appendix, we replicate all of these specifications using our Chilean trade transactions data, and show that we find the same qualitative and quantitative pattern of results.

5.1. Elasticities of substitution

In Table 1, we summarize our baseline estimates of the elasticities of substitution (σ_g^U, σ_g^F, σ^G). Since we estimate a product and firm elasticity for each sector, it would needlessly clutter the paper to report all of these elasticities individually. Therefore we report quantiles of the distributions of product and firm elasticities (σ_g^U, σ_g^F) across sectors and the single estimated elasticity of substitution across sectors (σ^G). The estimated product and firm elasticities are significantly larger than one statistically and always below eleven. We find a median estimated elasticity across products (σ_g^U) of 6.29, a median elasticity across firms (σ_g^F) of 2.66, and an elasticity across sectors (σ^G) of 1.36. Therefore, we find that products within firms, firms within sectors and sectors are indeed imperfect substitutes for one another.

Although we do not impose this restriction on the estimation, we find a natural ordering, in which varieties are more substitutable within firms than across firms, and firms are more substitutable within industries than across industries: $\hat{\sigma}_g^U > \hat{\sigma}_g^F > \hat{\sigma}^G$. We find that the product elasticity is significantly larger than the firm elasticity at the 5 percent level of significance for all sectors, and the firm elasticity is significantly larger than the sector elasticity at this significance level for all sectors as well.[14] Therefore, the data reject the special cases in which consumers only care about firm varieties ($\sigma_g^U = \sigma_g^F = \sigma^G$), in which varieties are perfectly substitutable within sectors ($\sigma_g^U = \sigma_g^F = \infty$), and in which products are equally differentiated within and across firms for a given sector ($\sigma_g^U = \sigma_g^F$). Instead, we find evidence of both firm differentiation within sectors and product differentiation within firms.

Our estimated elasticities of substitution are broadly consistent with those of other studies that have used similar data but different methodologies and/or nesting structures. In line with Broda and Weinstein (2006), we find lower elasticities of substitution as one moves to higher levels of aggregation. Our estimates of the product and firm elasticities (σ_g^F and σ_g^U) are only slightly smaller than those estimated by Hottman et al. (2016) using different data (U.S. barcodes versus internationally-traded HS products) and a different estimation methodology based on Feenstra (1994).[15] Although we cannot disclose the U.S. elasticities estimated using the HRW methodology because of census disclosure requirements, they are similar to those obtained in Table 1. Therefore, our estimated elasticities do not differ substantially from those obtained using other standard methodologies. As a check on the sensitivity of our estimated elasticities to the definition of categories, we re-estimated the product, firm, and sector elasticities using 6-digit instead of 4-digit NAICS codes as our definition of sectors. We find a similar pattern of results, with a median product elasticity of 6.20, a median firm elasticity of 2.70, and a sector elasticity of 1.47. As a check on the sensitivity of our results for comparative advantage to these estimated elasticities, we also report the results of a grid search over a range of alternative values for these elasticities in Section 5.3 below.

[14] In Figure A.5.1 in Section A.5.1 of the Online Appendix, we show the bootstrap confidence intervals for each sector.

[15] Our median estimates for the elasticities of substitution within and across firms of 6.3 and 2.7 respectively compare with those of 6.9 and 3.9 respectively in Hottman et al. (2016).

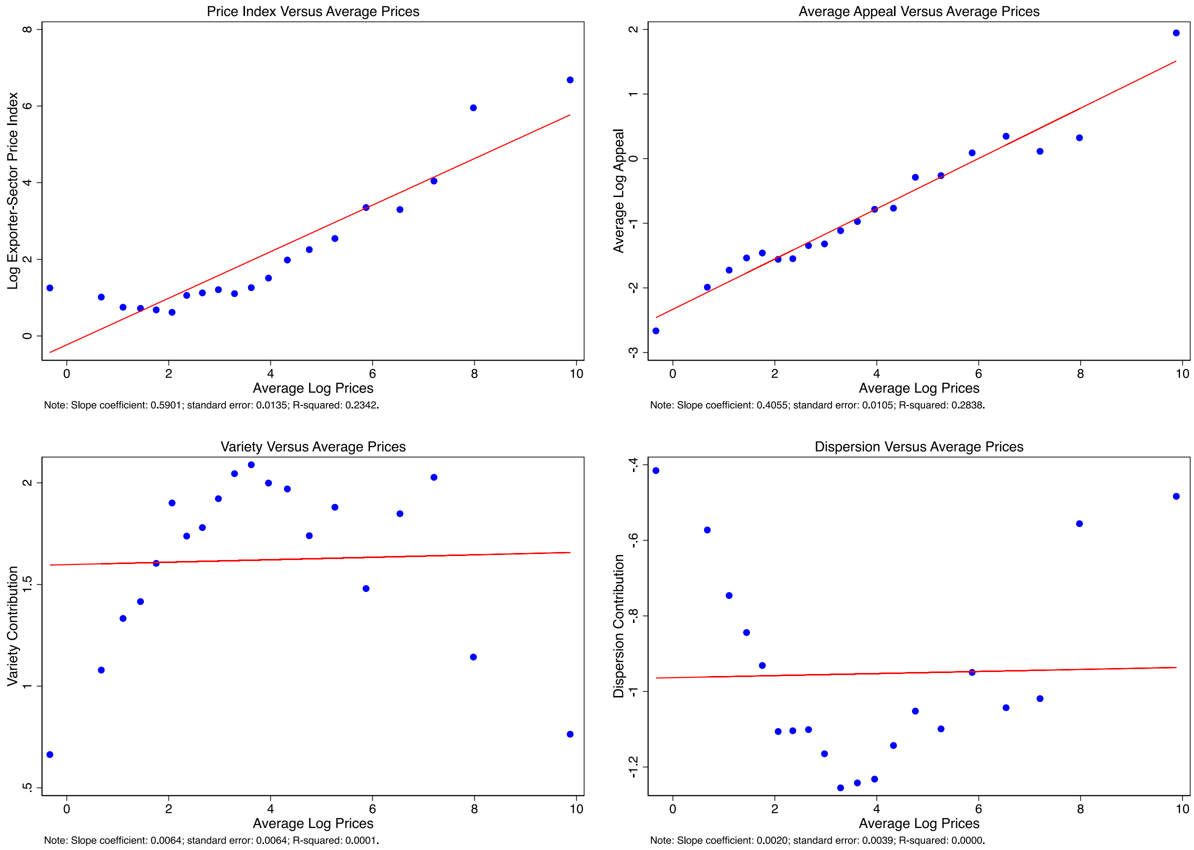

Fig. 1. U.S. exporter-sector price indexes and their components versus average log product prices, 2011. Note: Log exporter-sector price index and its components for U.S. imports in 2011 from Eq. (21); dispersion corresponds to the dispersion of appeal-adjusted prices; Blue dots show ventiles of the distribution; Red line shows the linear regression relationship between the variables.

5.2. Exporter price indexes across sectors and countries

We use these estimated elasticities (σ_g^U, σ_g^F, σ^G) to recover the structural residuals (φ_{ut}^U, φ_{ft}^F, φ_{jgt}^G) and solve for the exporter price indexes ($\mathbb{P}_{jigt}^E$) that summarize the cost of sourcing goods from each exporter and sector. A key implication of our framework is that these exporter price indexes depend not only on average prices, but also on average appeal, variety and the dispersion of appeal-adjusted prices. We now quantify the relative importance of each of these components.

In the four panels of Fig. 1, we display a bin scatter of the log of the exporter price index ($\ln \mathbb{P}_{jigt}^E$) and each of its components against average log product prices ($\mathbb{E}_{jigt}^{FU}\left[\ln P_{ut}^U\right]$), where the bins are twenty quantiles of each variable.[16] In each panel, we also show the regression relationship between the two variables based on the disaggregated (i.e., not binned) data. For brevity, we show results for the final year of our sample in 2011, but find the same pattern for other years in our sample. In the top-left panel, we compare the log exporter price index ($\ln \mathbb{P}_{jigt}^E$) to average log product prices ($\mathbb{E}_{jigt}^{FU}\left[\ln P_{ut}^U\right]$). In the special case in which firms and products are perfect substitutes within sectors ($\sigma_g^U = \sigma_g^F = \infty$) and there are no differences in appeal ($\varphi_{ft}^F = \varphi_{mt}^F$ for all f, m and $\varphi_{ut}^U = \varphi_{\ell t}^U$ for all u, ℓ), these two variables would be perfectly correlated. In contrast to these predictions, we find a positive but imperfect relationship, with an estimated regression slope of 0.59 and R^2 of 0.23. Therefore, the true cost of sourcing goods across countries and sectors can differ substantially from standard empirical measures of average prices.

In the remaining panels of Fig. 1, we explore the three sources of differences between the exporter price index and average log product prices. As shown in the top-right panel, exporter sectors with high average prices (horizontal axis) also have high average appeal (vertical axis), so that the impact of higher average prices in raising sourcing costs is partially offset by higher average appeal. This positive relationship between average prices and appeal is strong and statistically significant, with an estimated regression slope

[16] We use a bin scatter, because U.S. Census disclosure requirements preclude showing results for each exporter-sector using the U.S. data. In Section A.6.2 of the Online Appendix, we show results by exporter-sector using publicly-available Chilean data.

Table 2
U.S. Aggregate price growth 1998–2011.

US Aggregate price growth 1998–2011			
	Aggregate	Aggregate terms	With import terms
Aggregate price	0.22		
Import prices		0.12	
Domestic competitiveness		0.30	0.30
Non-Tradable competitiveness		−0.19	−0.19
Sector dispersion		0.00	0.00
Average prices			0.39
Product variety			−0.01
Product dispersion			0.00
Firm appeal			−0.02
Firm variety			−0.16
Firm dispersion			−0.05
Country-sector variety			0.00
Country-sector dispersion			−0.03

Note: Decomposition of the growth in the aggregate U.S. price index from 1998–2011 using Eqs. (29) and (30); dispersion corresponds to the dispersion of appeal-adjusted prices.

of 0.41 and R^2 of 0.28. This finding of higher average appeal for products with higher average prices is consistent with the quality interpretation of appeal stressed in Schott (2004), in which producing higher quality incurs higher production costs.[17]

In measuring appeal as a residual that shifts expenditure shares conditional on price, we follow a long line of research in trade and industrial organization. This approach is similar to that taken to measure productivity in the growth literature, in which total factor productivity is a residual that shifts output conditional on inputs. The substantial variation in firm exports conditional on price is the underlying feature of the data that drives our finding of an important role for appeal in Fig. 1. For plausible values of the elasticity of substitution, the model cannot explain this sales variation by price variation, and hence it is attributed to appeal. This result implies that the large class of trade models based on CES demand requires heterogeneity in appeal and costs to rationalize the observed data.

In the bottom-left panel of Fig. 1, we show that the contribution from the number of varieties to the exporter-sector price index exhibits an inverse U-shape, at first increasing with average prices, before later decreasing. This contribution ranges by more than two log points, confirming the empirical relevance of consumer love of variety. In contrast, in the bottom-right panel of Fig. 1, we show that the contribution from the dispersion of appeal-adjusted prices displays the opposite pattern of a U-shape, at first decreasing with average prices before later increasing. While the extent of variation is smaller than for the variety contribution, this term still fluctuates by around half a log point between its minimum and maximum value. Therefore, the imperfect substitutability of firms and products implies important contributions from the number of varieties and the dispersion in the characteristics of those varieties towards the true cost of sourcing goods across countries and sectors.

These non-conventional determinants are not only important in the cross-section but are also important for changes in the cost of sourcing goods over time. A common empirical question in macroeconomics and international trade is the effect of price shocks in a given sector and country on prices and real economic variables in other countries. However, it is not uncommon to find that measured changes in prices often appear to have relatively small effects on real economic variables, which has stimulated research on "elasticity puzzles" and the "exchange-rate disconnect". Although duality provides a precise mapping between prices and quantities, the actual price indexes used by researchers often differ in important ways from the formulas for price indexes from theories of consumer behavior. For example, as we noted earlier, our average price term is the log of the "Jevons Index", which is used by the U.S. Bureau of Labor Statistics (BLS) as part of its calculation of the consumer price index. Except in special cases, however, this average price term will not equal the theoretically-correct measure of the change in the unit expenditure function.

We first demonstrate the importance of this point for aggregate prices. In Table 2, we decompose the log change in the U.S. aggregate cost of living from 1998–11 using Eqs. (29) and (30). In the first column, we find that the aggregate U.S. price index increased by 0.22 log points over this time period. In the second column, we decompose this price change into four elements. First, the import price index rose by 0.12 log units which accounted for a little over half of the aggregate movement. Second, the value of imports rose as a share of tradables despite the rise in import prices, which implies that the exact price index of domestic tradables must have risen even more. This change in domestic competitiveness resulted in an increase in the price index by of an additional 0.3 log units. Offsetting this increase was a decline in the share of tradables in the US economy, which implies a relative decline in non-tradable prices that equaled a 0.19 log-unit decline in the U.S. aggregate price index. Finally, there was a negligible contribution from the dispersion of appeal-adjusted prices across sectors. Thus, our decomposition enables us to capture not only the impact of import prices on aggregate prices, but also the impact of relative movements in the price indexes of domestic tradables and non-tradables.

Interestingly, the 0.12 log-point increase in aggregate import prices is much less than the 0.41 log point change in import prices between 1998 and 2011 reported in the BLS's U.S. Import Price Index for All Commodities. We can see the reason for the difference

[17] This close relationship between appeal and prices is consistent the findings of a number of studies, including the analysis of U.S. barcode data in Hottman et al. (2016) and the results for Chinese footwear producers in Roberts et al. (2018).

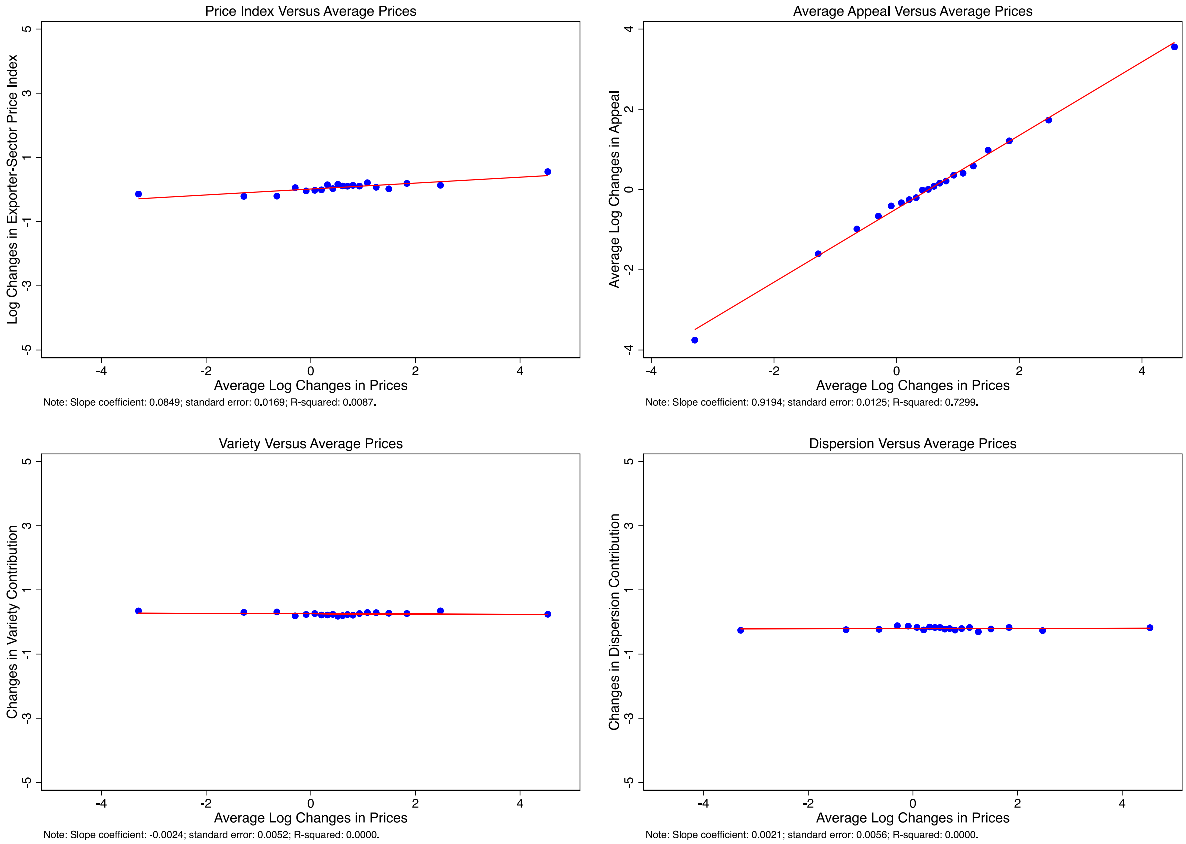

Fig. 2. Log changes in U.S. sector-exporter price indexes and their components versus average log changes in product prices, 1998–2011. Note: Changes in the log exporter-sector price index and its components for U.S. imports in 2011 from Eq. (22); dispersion corresponds to the dispersion of appeal-adjusted prices; Blue dots show ventiles of the distribution; Red line shows the linear regression relationship between the variables.

in the third column which expands our theoretical measure of the import price index into its components. The average log-price change, which equals the log of the Jevons index (the first term in Eq. (30)) rose by 0.39 log points over this time period: remarkably close to the 0.41 log point change reported in official series. Moreover, log changes in these two indexes are highly correlated in annual data as well ($\rho = 0.72$), which indicates that even at higher frequencies our Jevons index captures much of the variation in average import price changes as measured by the BLS. In other words, one obtains a very similar measure of import price increases regardless of whether one uses averages of log unit values or the price quotes used by the BLS in its Import Price Index.

As we have been emphasizing, however, this index does not capture many of the other forces that matter for cost-of-living changes in a theoretically-consistent price index. In particular, we find that the positive contribution from higher average prices of imported goods was offset by a substantial negative contribution from firm variety (see Eq. (30) for the definition of each term). This expansion in firm import variety reduced the cost of imported goods by around 0.16 log points. Changes in average firm appeal and the dispersion of appeal-adjusted prices across firms also acted to reduce aggregate import prices over this period. As a result, the true increase in the cost of imported goods from 1998–2011 was only 0.12 log points, less than one third the value implied by the conventional Jevons Index. In other words, a theory-based measure of aggregate import prices behaves very differently from one based only on average prices.

We next show that this point applies not only to aggregate import prices but also to the changes in exporter price indexes ($\Delta \ln \mathbb{P}^{E}_{jigt}$) that summarize the cost of sourcing goods across countries and sectors. Fig. 2 displays the same information as in Fig. 1, but for log changes from 1998–2011 rather than for log levels in 2011. In changes, the correlation between average prices and the true model-based measure of the cost of sourcing goods is much weaker (top-left panel) and the role for appeal is even greater (top-right panel). Indeed, the slope for the regression of average log changes in appeal on average log changes in prices is 0.92, indicating that most price changes are almost completely offset by appeal changes. This result suggests that the standard assumption of no shifts in appeal, which underlies standard price indexes such as the Sato-Vartia, is problematic for Harmonized System (HS) product categories that can experience substantial changes in quality over time. Price and appeal shifts are strongly positively correlated, consistent with increases in appeal in part capturing increases in product quality that are costly to achieve.

Table 3
Variance decomposition U.S. RCA.

	Log level RCA 2011		Log change RCA 1998–2011	
	Firm-level decomposition	Product-level decomposition	Firm-level decomposition	Product-level decomposition
Firm price index	0.094	–	−0.005	–
Firm appeal	0.220	0.220	0.422	0.422
Firm variety	0.324	0.324	0.501	0.501
Firm dispersion	0.362	0.362	0.082	0.082
Product prices	–	0.065	–	−0.048
Product variety	–	0.014	–	0.037
Product dispersion	–	0.014	–	0.007

Note: Variance decomposition for the log level of RCA in 2011 and the log change in RCA from 1998–2011 (from Eq. (34)); dispersion corresponds to the dispersion of appeal-adjusted prices.

5.3. Trade patterns

We now use our results connecting RCA to relative exporter price indexes to examine the importance of the different components of these price indexes for comparative advantage across countries and sectors. We start with the decompositions of the level and change of RCA in Eqs. (26) and (27) in Section 2.10.1 above. We use a regression-based variance decomposition that is relatively common in the international trade and macroeconomics literatures following Klenow and Rodríguez-Clare (1997) and Bernard et al. (2009a). We assess the contribution of each mechanism by regressing each component of RCA on the overall value of RCA for both levels (Eq. (26)) and log changes (Eq. (27)). For the level of RCA, we have:

$$\begin{aligned}
\ln\left(RCA^{P}_{jigt}\right) &= \alpha_P + \beta_P \ln\left(RCA_{jigt}\right) + u^{P}_{jigt}, \\
\ln\left(RCA^{\varphi}_{jigt}\right) &= \alpha_\varphi + \beta_\varphi \ln\left(RCA_{jigt}\right) + u^{\varphi}_{jigt}, \\
\ln\left(RCA^{S}_{jigt}\right) &= \alpha_S + \beta_S \ln\left(RCA_{jigt}\right) + u^{S}_{jigt}, \\
\ln\left(RCA^{N}_{jigt}\right) &= \alpha_N + \beta_N \ln\left(RCA_{jigt}\right) + u^{N}_{jigt}.
\end{aligned} \tag{34}$$

where observations are exporters i and sectors g for a given importer j and year t. Since the sum of the dependent variables equals the independent variable, by the properties of OLS, $\beta_P + \beta_\varphi + \beta_S + \beta_N = 1$, and the relative value of each coefficient tells us the relative importance of each component of exporter price indexes. This regression-based variance decomposition allocates the covariance terms equally across the components of the decomposition, as shown in Section A.5.2 of the Online Appendix. We also report a robustness test using an alternative variance decomposition following Grömping (2007) in that same section of the Online Appendix.

In Table 3, we report the results of these decompositions for both levels of RCA (Columns (1)-(2)) and changes of RCA (Columns (3)-(4)). In Columns (1) and (3), we undertake these decompositions down to the firm level. In Columns (2) and (4), we undertake them all the way down to the product level. For brevity, we concentrate on the results of the full decomposition in Columns (2) and (4). We find that average prices are comparatively unimportant in explaining patterns of trade. In the cross-section, average product prices account for 6.5 percent of the variation in RCA. In the time-series, we find that higher average prices are more than offset by higher appeal, resulting in a negative contribution of 4.8 percent from prices to changes in RCA. These results reflect the low correlations between average prices and exporter price indexes seen in the last section. If average prices are weakly correlated with exporter price indexes, they are unlikely to matter much for RCA, because RCA is determined by relative exporter price indexes. We find a similar pattern of results using the alternative variance decomposition from Grömping (2007) in Section A.5.2 of the Online Appendix, though with marginally higher contributions from prices.

One potential explanation for the relative unimportance of average prices in explaining trade patterns arises in the neoclassical Heckscher–Ohlin model. In an international trade equilibrium characterized by factor price equalization, relative goods prices are the same across all countries, and patterns of trade across countries and sectors are entirely explained by relative factor endowments. But we find substantial differences in average prices across countries within sectors, which is inconsistent with factor price equalization in the Heckscher–Ohlin model. More importantly, we show below that we find substantial contributions to observed trade patterns from average appeal, variety and the dispersion in appeal-adjusted prices, which do not feature in standard interpretations of the Heckscher–Ohlin model.

In particular, we find that average appeal is over three times more important than average prices, with a contribution of 22 percent for levels of RCA and 42 percent for changes in RCA in Table 3. In principle, one could reinterpret the predictions of neoclassical trade models as predictions for appeal-adjusted relative prices. However, at a minimum, this involves a substantial change in the interpretation of these models, suggesting the importance of quality differences, as captured in our measures of appeal, and emphasized in Sutton (1991), Crozet et al. (2012) and Manova and Zhang (2012). Furthermore, it is at least not obvious that the determinants of appeal are exactly the same as those of prices, with sunk costs often playing a prominent role in models of endogenous quality.

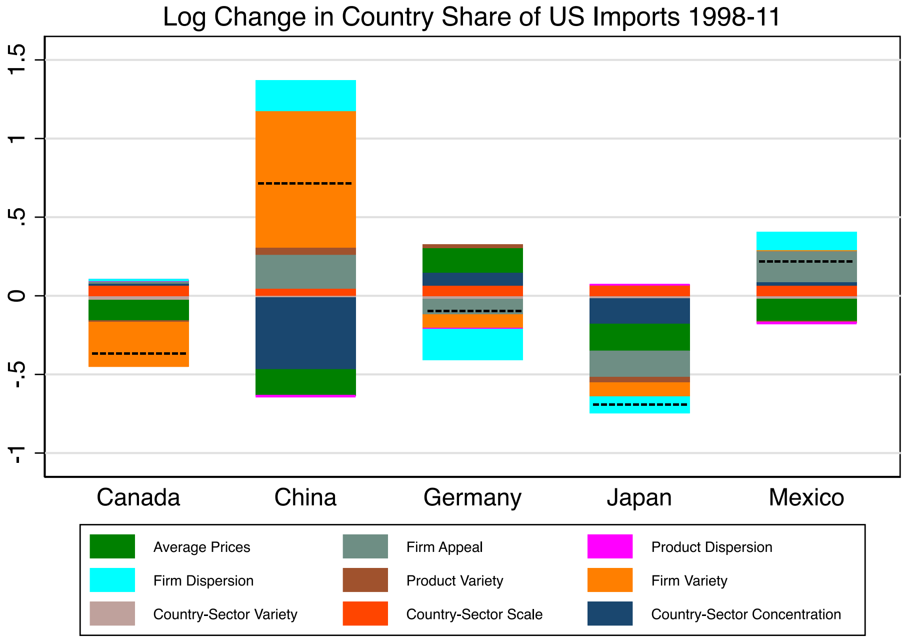

Fig. 3. Country aggregate shares of U.S. imports. Note: Decomposition of exporting countries shares of total U.S. imports from Eq. (28); dispersion corresponds to the dispersion of appeal-adjusted prices.

By far the most important of the different mechanisms for trade in Table 3 is firm variety, which accounts for 32 and 50 percent of the level and change of RCA respectively. These findings for firm variety are consistent with research that emphasizes the role of the extensive margin in understanding patterns of trade, including Hummels and Klenow (2005), Chaney (2008) and Kehoe and Ruhl (2013). But we also find a notable contribution from the dispersion of appeal-adjusted prices across firms, which accounts for 36 percent of the variation in RCA in the cross-section and 8 percent of this variation over time. These results are consistent with a substantial role for producer heterogeneity, as emphasized in the large literature on heterogeneous firms following Melitz (2003), as reviewed in Bernard et al. (2007a) and Melitz and Redding (2014).

More broadly, this pattern of empirical results is consistent with theoretical frameworks in which comparative advantage operates not only through prices but also through the mass of firms and the distributions of productivity and appeal across firms, such as Bernard et al. (2007b). While recent empirical studies have documented substantial churning in patterns of comparative advantage over time, as in Freund and Pierola (2015) and Hanson et al. (2015), our findings imply that this churning largely occurs through changes in average appeal and firm entry/exit. The dominance of these two components of changes in average appeal and firm entry/exit suggests the relevance of theoretical frameworks in which comparative advantage arises from endogenous investments in product and process innovation, as in Grossman and Helpman (1991).

We find that our results for comparative advantage are robust across a number of different specifications. As a check on the sensitivity of our findings to the definition of categories, we replicated our entire analysis using a definition of sectors based of 6-digit instead of 4-digit NAICS codes. Using this different definition, we find a similar pattern of results as in our baseline specification, with average appeal accounting for 23 and 46 percent of the level and change of RCA, and firm variety making up 34 and 47 percent. As a further robustness check, we undertook a grid search over the range of plausible values for the elasticities of substitution across firms and products. In particular, we consider values of σ_g^F from 2 to 8 (in 0.5 increments) and values of σ_g^U from $(\sigma_g^F + 0.5)$ to 20 in 0.5 increments, while holding σ^G constant at our estimated value, which respects our estimated ranking that $\sigma_g^U > \sigma_g^F > \sigma^G$. As shown in Section A.5.4 of the Online Appendix, the contributions from firm variety and the dispersion of appeal-adjusted prices across firms are invariant across these parameter values, because the elasticities of substitution cancel from these two terms. In contrast, the contributions from average prices and average appeal are increasing and decreasing in σ_g^F respectively. Nevertheless, across the grid of parameter values, we find that average prices account for less than 25 percent of the level of the RCA and less than 10 percent of the changes in RCA. Therefore, our finding that the relative price indexes that determine comparative advantage depart substantially from average prices is robust across the range of plausible elasticities of substitution.

We now show that the non-conventional forces of variety, average appeal, and the dispersion of appeal-adjusted prices are also important for understanding aggregate U.S. imports from its largest suppliers. In Fig. 3, we show the time-series decompositions of aggregate import shares from Eq. (28) for the top-five trade partners of the United States. We find that most of the increase in China's market share over the sample period occurs through increases in the number of firm varieties (orange), average firm appeal (dark gray) and the dispersion of appeal-adjusted prices across firm varieties (light blue).[18] In contrast, average product prices (green) increased more rapidly for China than for the other countries in our sample, which worked to reduce China's market share. Therefore, the reasons for the explosive growth of Chinese exports were not cheaper Chinese exports, but rather substantial firm entry (variety), appeal upgrading, and improvements in the performance of leading firms relative to lagging firms (the dispersion of appeal-adjusted prices). For Canada, we find that firm exit (orange) makes the largest contribution to the decline in its import share. For Germany, Japan and Mexico, we find substantial contributions from average firm appeal (gray) and the dispersion of appeal-adjusted prices across firms (light blue), which are large relative to the contributions from average prices. Therefore, consistent with our results for sectoral patterns of trade above, we find that most of the change in aggregate import shares is explained by forces other than standard empirical measures of average prices.

Taken together, the results of this section highlight the role of imperfect substitutability for comparative advantage and the aggregate volume of trade. Both are determined by relative price indexes that summarize the cost of sourcing goods from each country and sector. In a world in which goods are imperfect substitutes, these relative price indexes cannot be inferred solely from conventional measures of average prices. Instead, they also depend on the non-conventional forces of the number of varieties, appeal upgrading, and the performance of leading relative to lagging varieties.

5.4. Additional theoretical restrictions

We now compare our approach, which exactly rationalizes both micro and macro trade data, with special cases of this approach that impose additional theoretical restrictions. As a result of these additional theoretical restrictions, these special cases no longer exactly rationalize the micro trade data, and we quantify the implications of these departures from the micro data for macro trade patterns and prices.

No changes in appeal. Almost all existing theoretical research with CES demand in international trade is encompassed by the Sato-Vartia price index, which assumes no shifts in appeal for common varieties. Duality suggests that there are two ways to assess the importance of this assumption. First, we can work with a price index and examine how a CES price index that allows for shifts in appeal (i.e., the UPI in Eq. (20)) differs from a CES price index that does not allow for these shifts in appeal (i.e., the Sato-Vartia index). Since the common goods component of the UPI (CG-UPI) and the Sato-Vartia indexes are identical in the absence of shifts in appeal, the difference between them is a metric for how important shifts in appeal are empirically. Second, we can substitute each of these price indexes into Eq. (25) for revealed comparative advantage (RCA), and examine how important the assumption of no shifts in appeal is for understanding patterns of trade. Since the UPI perfectly rationalizes the data, any deviation from the data arising from using a different price index must reflect the effect of the restrictive assumption used in the index's derivation. In order to make the comparison fair, we need to also adjust the Sato-Vartia index for variety changes, which we do by using the Feenstra (1994) index, which is based on the same no-appeal-shifts assumption for common goods, but adds the variety correction term given in Eq. (20) to incorporate entry and exit.

In Fig. 4, we report the results of these comparisons. The top two panels consider exporter price indexes, while the bottom two panels examine RCA. In the top-left panel, we show a bin scatter of the Sato-Vartia exporter price index (on the vertical axis) against the common goods exporter price index (the CG-UPI on the horizontal axis), where the bins are twenty quantiles of each variable.[19] We also show the regression relationship between the two variables based on the disaggregated (i.e. not binned) data. If the assumption of time-invariant appeal were satisfied in the data, these two indexes would be perfectly correlated with one another and aligned on the 45-degree line. However, we find little relationship between them. The reason is immediately apparent if one recalls the top-right panel of Fig. 2, which shows that price shifts are strongly positively correlated with appeal shifts. The Sato-Vartia price index fails to take into account that higher prices are typically offset by higher appeal. In the top-right panel, we compare the Feenstra exporter price index (on the vertical axis) with our overall exporter price index (the UPI on the horizontal axis). These two price indexes have exactly the same variety correction term, but use different common goods price indexes (the CG-UPI and Sato-Vartia indexes respectively). The importance of the variety correction term as a share of the overall exporter price index accounts for the improvement in the fit of the relationship. However, the slope of the regression line is only around 0.5, and the regression R^2 is about 0.1. Therefore, the assumption of no shifts in appeal for existing goods results in substantial deviations between the true and measured costs of sourcing goods from an exporter and sector.

In the bottom left panel, we compare predicted changes in RCA based on relative exporter Sato-Vartia price indexes (on the vertical axis) against actual changes in RCA (on the horizontal axis). As the Sato-Vartia price index has only a weak correlation with the UPI, we find that it has little predictive power for changes in RCA, which are equal to relative changes in the UPI across exporters and sectors. Hence, observed changes in trade patterns are almost uncorrelated with the changes predicted under the assumption of no shifts in appeal and no entry/exit of firms and products. In the bottom right panel, we compare actual changes in RCA (on the horizontal axis) against predicted changes in RCA based on relative exporter Feenstra price indexes (on the vertical axis). The improvement in the fit of the relationship attests to the importance of adjusting for entry and exit. However, again the slope of the regression line is only around 0.5 and the regression R^2 is less than 0.1. Therefore, even after adjusting for the shared entry and exit term, the assumption of no shifts in appeal for existing goods can generate predictions for changes in trade patterns that diverge substantially from those observed in the data.

[18] Our finding of an important role for firm entry for China is consistent with the results for export prices in Amiti et al. (2020). However, their price index is based on the Sato-Vartia formula, which abstracts from changes in appeal for surviving varieties, and they focus on Chinese export prices rather on than trade patterns.

[19] Again we use a bin scatter, because U.S. Census disclosure requirements preclude showing results for each exporter-sector using the U.S. data. In Section A.6.4 of the Online Appendix, we show results by exporter-sector using publicly-available Chilean data.

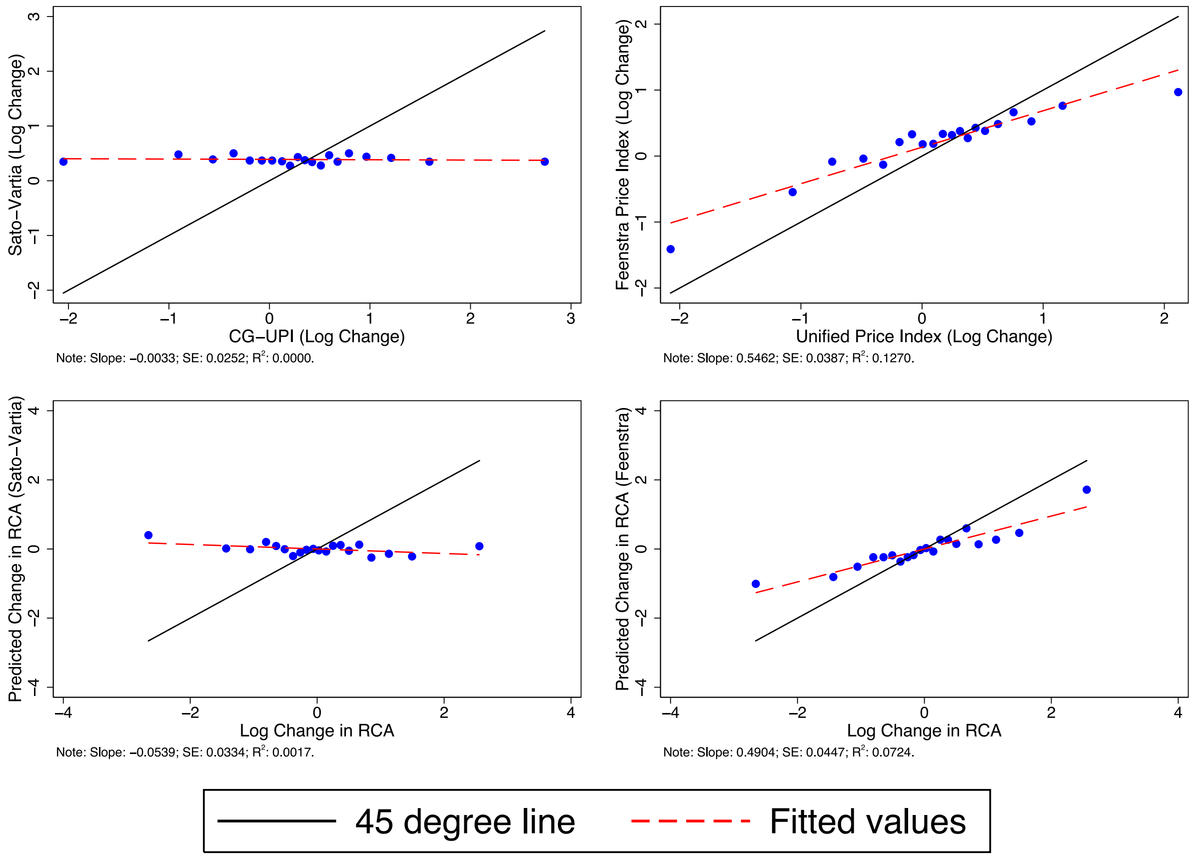

Fig. 4. Sector-exporter price indexes with time-invariant appeal (Vertical axis) versus time-varying appeal (Horizontal axis) for the U.S. Note: Log changes in sector-exporter price indexes allowing for changes in appeal (common goods unified price index (CG-UPI)) and assuming no changes in appeal (Sato-Vartia price index); Feenstra (1994) price index adjusts the Sato-Vartia price index for changes in variety; unified price index (UPI) adjusts the common goods unified price index (CG-UPI) for changes in variety.

Additional functional form restrictions. We now examine the implications of imposing additional functional form restrictions on the supply-side of the economy. In particular, an important class of existing trade theories assumes not only a constant demand-side elasticity but also a constant supply-side elasticity, as reflected in the assumption of Fréchet or Pareto productivity distributions.[20] As our approach uses only demand-side assumptions, we can examine the extent to which these additional supply-side restrictions are satisfied in the data. In particular, we compare the observed data for firm sales and our model solutions for the firm price index and firm appeal ($\ln V_{ft}^F \in \left\{ \ln \mathbb{X}_{ft}^F, \ln P_{ft}^F, \ln \varphi_{ft}^F \right\}$) with their theoretical predictions under alternative supply-side distributional assumptions.

To derive these theoretical predictions, we use the QQ estimator of Kratz and Resnick (1996), as introduced into the international trade literature by Head et al. (2014). This QQ estimator compares the empirical quantiles in the data with the theoretical quantiles implied by alternative distributional assumptions. As shown in Section A.5.5 of the Online Appendix, under the assumption that V_{ft}^F has a Pareto distribution, we obtain the following theoretical prediction for the quantile of the logarithm of that variable:

$$\ln\left(V_{ft}^F\right) = \ln \underline{V}_{jigt}^F - \frac{1}{a_g^V} \ln\left[1 - \mathcal{F}_{jigt}\left(V_{ft}^F\right)\right], \tag{35}$$

where $\mathcal{F}_{jigt}(\cdot)$ is the cumulative distribution function; $\ln \underline{V}_{jigt}^F$ is the lower limit of the support of the Pareto distribution, which is a constant across firms f for a given importer j, exporter i, sector g and year t; a_g^V is the shape parameter of this distribution, which we allow to vary across sectors g.

[20] Ricardian trade models following Eaton and Kortum (2002) frequently assume a Fréchet productivity distribution, as in Costinot et al. (2012). The firm heterogeneity literature following Melitz (2003) often assumes a Pareto productivity distribution, as in Chaney (2008) and Bernard et al. (2011). Eaton et al. (2011) combines the assumption of a Pareto productivity distribution with stochastic shocks to tastes and fixed costs that are log normally distributed. Fernandes et al. (2022) assumes a log normal distribution of productivity. Arkolakis et al. (2012) provides macro restrictions on preferences, technology and market structure under which the import demand system exhibits a constant elasticity with respect to trade costs.

We estimate Eq. (35) by OLS using the empirical quantile for $\ln\left(V_{ft}^{F}\right)$ on the left-hand side and the empirical estimate of the cumulative distribution function for $\mathcal{F}_{jigt}\left(V_{ft}^{F}\right)$ on the right-hand side, as discussed further in the Online Appendix. We estimate this regression for each sector across foreign firms (allowing the slope coefficient a_{g}^{V} to vary across sectors) and including fixed effects for each exporter-year-sector combination (allowing the intercept $\ln \underline{V}_{jigt}^{F}$ to vary across exporters, sectors and time). The fitted values from this regression correspond to the predicted theoretical quantiles, which we compare to the empirical quantiles in the data. Under the null hypothesis of a Pareto distribution, there should be a linear relationship between the theoretical and empirical quantiles that coincides with the 45-degree line.

To assess the empirical validity of this theoretical prediction, we estimate Eq. (35) for two separate subsamples: firms with values below the median for each exporter-sector-year cell and firms with values above the median for each exporter-sector-year cell. Under the null hypothesis of a Pareto distribution, the estimated slope coefficient $1/a_{g}^{V}$ should be the same for firms below and above the median.[21] As shown in Section A.5.5 of the Online Appendix, we strongly reject this null hypothesis of a Pareto distribution for all three variables, with substantial differences in the estimated coefficients below and above the median, which are statistically significant at conventional levels.

To provide a point of comparison, we also consider the log-normal distributional assumption. As shown in Section A.5.5 of the Online Appendix, we obtain the following theoretical prediction for the quantile of the logarithm of a variable V_{ft}^{F} under this distributional assumption:

$$\ln\left(V_{ft}^{F}\right) = \kappa_{jigt}^{V} + \chi_{g}^{V}\Phi^{-1}\left(\mathcal{F}_{jigt}\left(V_{ft}^{F}\right)\right). \tag{36}$$

where $\Phi^{-1}(\cdot)$ is the inverse of the normal cumulative distribution function; κ_{jigt}^{V} and χ_{g}^{V} are the mean and standard deviation of the log variable, such that $\ln\left(V_{ft}^{F}\right) \sim \mathcal{N}\left(\kappa_{jigt}^{V}, \left(\chi_{g}^{V}\right)^{2}\right)$; we make analogous assumptions about these two parameters as for the Pareto distribution above; we allow the parameter controlling the mean (κ_{jigt}^{V}) to vary across exporters i, sectors g and time t for a given importer j; we allow the parameter controlling dispersion (χ_{g}^{V}) to vary across sectors g.

Again we estimate Eq. (36) by OLS using the empirical quantile for $\ln\left(V_{ft}^{F}\right)$ on the left-hand side and the empirical estimate of the cumulative distribution function for $\mathcal{F}_{jigt}\left(V_{ft}^{F}\right)$ on the right-hand side. We estimate this regression for each sector across foreign firms (allowing the slope coefficient χ_{g}^{V} to vary across sectors) and including fixed effects for each exporter-year-sector combination (allowing the intercept κ_{jigt}^{V} to vary across exporters, sectors and time). As shown in Section A.5.5 of the Online Appendix, we find that the log-normal distributional assumption provides a closer approximation to the data than the Pareto distributional assumption. Consistent with Bas et al. (2017) and Fernandes et al. (2022), we find smaller departures from the predicted linear relationship between the theoretical and empirical quantiles for a log-normal distribution than for a Pareto distribution. Nevertheless, we reject the null hypothesis of a log-normal distribution at conventional significance levels for all three variables for the majority of industries, with substantial differences in estimated coefficients above and below the median. Therefore, for both the Pareto and log normal distributions, we reject these additional supply-side restrictions.

6. Conclusions

Leading theories of international trade predict that changes in comparative advantage and aggregate trade shares occur through changes in prices, product appeal (including quality), product variety and producer heterogeneity. Researchers in international trade face three key challenges in taking these theoretical predictions to the data. First, prices are not typically measured at the industry level, but are rather observed for thousands of disaggregated products within industries, which raises the challenge of how to aggregate from the product to the industry level. Second, product appeal is typically not directly measured, which raises the question of how to control for unobserved changes in quality and other product characteristics over time. Third, new products enter and existing products exit, which raises the issue of how to appropriately weight the contribution of these entering and exiting products in understanding changes in industry comparative advantage and aggregate trade shares over time.

We develop a quantitative framework based on nested constant elasticity of substitution (CES) preferences that simultaneously addresses each of these challenges. We show how to aggregate data on the prices of thousands of disaggregated traded products to obtain industry and aggregate price indexes, which take into account average prices, average appeal, entry and exit (variety) and the dispersion in appeal-adjusted prices (heterogeneity). Our procedure allows for unobserved differences in composition within observed product categories, which are captured in our measures of product appeal from our demand system inversion. We show how to compute aggregate price indexes even in the absence of disaggregated data on domestic prices within traded sectors or on prices in non-traded sectors.

Using our U.S. data, we estimate a median elasticity of substitution across products of 6.29, a median elasticity across firm divisions of 2.66, and an elasticity across sectors of 1.36. We use our nested CES preference structure to define a measure of revealed comparative advantage (RCA) that can be exactly decomposed into the contributions of different mechanisms in leading theories of international trade. We show that much of the observed variation in patterns of trade is driven by variety, heterogeneity and

[21] U.S. Census disclosure requirements preclude showing the quantiles for individual foreign firms using the U.S. data. In Figures A.6.7 and A.6.8 in Section A.6.4 of the Online Appendix, we show firm quantiles using publicly-available Chilean data.

appeal. Firm entry/exit and the dispersion in appeal-adjusted prices each account for around one third of the cross-section variation in patterns of trade across countries and sectors. By contrast, average appeal and average prices contribute just over 20 percent and just under 10 percent, respectively. For changes in trade patterns over time, the results are even more stark. Firm entry/exit and average appeal each account for around 45 percent of the variation, with the dispersion of appeal-adjusted prices making up most of the rest. These empirical findings suggest the relevance of theories in which comparative advantage operates not only through average prices, but also through the mass of firms and the distributions of productivity and appeal across firms.

We demonstrate that these findings also have implications for the measurement of import price indexes. We show that our average price term has a similar functional form to the Bureau of Labor Statistics (BLS) import price index and tracks this official index closely in the data (with a correlation coefficient of 0.72), even though we measure prices using unit values rather than price quotes. Nevertheless, the large contributions from variety, average appeal and the dispersion in appeal-adjusted prices imply that the BLS import price index has little correlation with our theoretically-consistent import price index. Finally, we show that these same forces of variety, average appeal and the dispersion in appeal-adjusted prices account for much of the observed changes in countries aggregate shares of U.S. imports, including the dramatic rise in China's import penetration over our sample period. Again these results emphasize the role of non-price determinants of the aggregate volume of trade between countries.

Taken together, our findings highlight the role of product differentiation in shaping patterns of international trade, including the number of varieties, the average appeal of those varieties, and the heterogeneity in the characteristics of those varieties.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jinteco.2024.103910.

References

Adão, Rodrigo, Arkolakis, Costas, Ganapati, Sharat, 2020. Aggregate Implications of Firm Heterogeneity: A Nonparametric Analysis of Monopolistic Competition Trade Models. NBER Working Paper, 28081.

Adão, Rodrigo, Costinot, Arnaud, Donaldson, Dave, 2017. Nonparametric counterfactual predictions in neoclassical models of international trade. Amer. Econ. Rev. 107 (3), 633–689.

Amiti, Mary, Dai, Mi, Feenstra, Robert, Romalis, John, 2020. How did China's WTO entry benefit U.S. consumers? J. Int. Econ. 126, 103339.

Amiti, Mary, Davis, Donald R., 2009. What's behind volatile import prices from China? Curr. Issues Econom. Finance 15 (1), 1–7.

Arkolakis, Costas, Costinot, Arnaud, Rodríguez-Clare, Andres, 2012. New trade models, same old gains. Amer. Econ. Rev. 102 (1), 94–130.

Armington, Paul S., 1969. A theory of demand for products distinguished by place of production. Int. Monet. Fund Staff Pap. 16 (1), 159–178.

Atkeson, Andrew, Burstein, Ariel, 2008. Pricing to market, trade costs and international relative prices. Amer. Econ. Rev. 98, 1998–2031.

Atkin, David, Donaldson, Dave, 2015. Who's Getting Globalized? The Size and Implications of Intra-National Trade Costs. NBER Working Paper, 21439.

Atkin, David, Faber, Benjamin, Gonzalez-Navarro, Marco, 2018. Retail globalization and household welfare: Evidence from Mexico. J. Polit. Econ. 126 (1), 1–73.

Balassa, Bela, 1965. Trade liberalization and revealed comparative advantage. Manch. Sch. Econ. Soc. Stud. 33, 99–123.

Bas, Maria, Mayer, Thierry, Thoenig, Mathias, 2017. From micro to macro: Demand, supply and heterogeneity in the trade elasticity. J. Int. Econ. 108, 1–19.

Bernard, Andrew B., Bradford Jensen, J., Redding, Stephen J., Schott, Peter K., 2007a. Firms in international trade. J. Econ. Perspect. 21 (3), 105–130.

Bernard, Andrew B., Bradford Jensen, J., Redding, Stephen J., Schott, Peter K., 2009a. The margins of U.S. trade. Am. Econ. Rev. Pap. Proc. 99 (2), 487–493.

Bernard, Andrew B., Bradford Jensen, J., Schott, Peter K., 2009b. Importers, exporters and multinationals: A portrait of firms in the U.S. that trade goods. In: Dunne, T., Jensen, J.B., Roberts, M.J. (Eds.), Producer Dynamics: New Evidence from Micro Data. Chicago University Press, Chicago.

Bernard, Andrew B., Redding, Stephen J., Schott, Peter K., 2007b. Comparative advantage and heterogeneous firms. Rev. Econom. Stud. 74 (1), 31–66.

Bernard, Andrew B., Redding, Stephen J., Schott, Peter K., 2010. Multi-product firms and product switching. Amer. Econ. Rev. 100 (1), 70–97.

Bernard, Andrew B., Redding, Stephen J., Schott, Peter K., 2011. Multiproduct firms and trade liberalization. Q. J. Econ. 126 (3), 1271–1318.

Broda, Christian, Weinstein, David E., 2006. Globalization and the gains from variety. Q. J. Econ. 121, 541–586.

Broda, Christian, Weinstein, David E., 2010. Product creation and destruction: Evidence and price implications. Amer. Econ. Rev. 100, 691–723.

Caliendo, Lorenzo, Parro, Fernando, 2015. Estimates of the trade and welfare effects of NAFTA. Rev. Econom. Stud. 82 (1), 1–44.

Chaney, Thomas, 2008. Distorted gravity: The intensive and extensive margins of international trade. Amer. Econ. Rev. 98 (4), 1707–1721.

Costinot, Arnaud, Donaldson, Dave, Komunjer, Ivana, 2012. What goods do countries trade? A quantitative exploration of ricardo's ideas. Rev. Econom. Stud. 79, 581–608.

Crozet, Matthieu, Head, Keith, Mayer, Thierry, 2012. Quality sorting and trade: Firm-level evidence for french wine. Rev. Econom. Stud. 79 (2), 609–644.

De Loecker, Jan, Goldberg, Penny, 2014. Firm performance in a global market. Annu. Rev. Econ. 6, 201–227.

Dhingra, Swati, 2013. Trading away wide brands for cheap brands. Amer. Econ. Rev. 103 (6), 2554–2584.

Di Comite, F., Thisse, J., Vandenbussche, H., 2014. Verti-zontal differentiation in export markets. J. Int. Econ. 93, 50–66.

Eaton, Jonathan, Kortum, Samuel S., 2002. Technology, geography, and trade. Econometrica 70 (5), 1741–1779.

Eaton, Jonathan, Kortum, Samuel S., Kramarz, Francis, 2011. An anatomy of international trade: Evidence from french firms. Econometrica 79 (5), 1453–1498.

Eckel, Carsten, Peter Neary, J., 2010. Multi-product firms and flexible manufacturing in the global economy. Rev. Econom. Stud. 77, 188–217.

Faber, Benjamin, Fally, Thibault, 2022. Firm heterogeneity in consumption baskets: Evidence from home and store scanner data. Rev. Econom. Stud. 89 (3), 1420–1459.

Feenstra, Robert C., 1994. New product varieties and the measurement of international prices. Amer. Econ. Rev. 84, 157–177.

Feenstra, Robert C., Luck, Philip, Obstfeld, Maurice, Russ, Katheryn N., 2018. In search of the armington elasticity. Rev. Econ. Stat. 100 (1), 135–150.

Feenstra, Robert C., Ma, Hong, 2008. Optimal choice of product scope for multiproduct firms. In: Helpman, Elhanan, Marin, Dalia, Verdier, Thierry (Eds.), The Organization of Firms in a Global Economy. Harvard University Press, Cambridge MA, pp. 173–199, (Chapter 6).

Feenstra, Robert C., Romalis, John, 2014. International prices and endogenous quality. Q. J. Econ. 129 (2), 477–527.

Fernandes, Ana M., Klenow, Peter J., Meleshchuk, Sergii, Pierola, Martha Denisse, Rodríguez-Clare, Andrés, Meleshchuk, Sergii, 2022. The intensive margin in trade: How big and how important? Am. Econ. J.: Macroecon. forthcoming.

Foster, Lucia, Haltiwanger, John, Syverson, Chad, 2008. Reallocation, firm turnover, and efficiency: Selection on productivity or profitability? Amer. Econ. Rev. 98 (1), 394–425.

Freund, Caroline, Pierola, Martha Denisse, 2015. Export superstars. Rev. Econ. Stat. 97 (5), 1023–1032.

Grömping, Ulrike, 2007. Estimators of relative importance in linear regression based on variance decomposition. Amer. Statist. 61 (2), 139–147.

Grossman, Gene, Helpman, Elhanan, 1991. Innovation and Growth in the Global Economy. MIT Press, Cambridge.

Hallak, Juan Carlos, Schott, Peter K., 2011. Estimating cross-country differences in product quality. Q. J. Econ. 126, 417–474.

Handbury, Jessie, 2021. Are poor cities cheap for everyone? Non-homotheticity and the cost of living across U.S. cities. Econometrica 89 (6), 2679–2715.

Hanson, Gordon H., Lind, Nelson, Muendler, Marc-Andreas, 2015. The Dynamics of Comparative Advantage. NBER Working Paper, 21753.

Head, Keith, Mayer, Thierry, Thoenig, Mathias, 2014. Welfare and trade without Pareto. Am. Econ. Rev. Pap. Proc. 104 (5), 310–316.

Helpman, Elhanan, Krugman, Paul R., 1985. Market Structure and Foreign Trade: Increasing Returns, Imperfect Competition and the International Economy. MIT Press, Cambridge MA.

Hottman, Colin, Redding, Stephen J., Weinstein, David E., 2016. Quantifying the sources of firm heterogeneity. Q. J. Econ. 131 (3), 1291–1364.

Hummels, David, Klenow, Peter J., 2005. The variety and quality of a nation's exports. Amer. Econ. Rev. 95 (3), 704–723.

Kamal, Fariha, Krizan, C.J, Monarch, Ryan, 2015. Identifying Foreign Suppliers in U.S. Merchandise Import Transactions. Center for Economic Studies Working Paper, 15-11, Bureau of the Census.

Kehoe, Timothy J., Ruhl, Kim J., 2013. How important is the new goods margin in international trade. J. Polit. Econ. 121 (2), 2013.

Khandelwal, Amit K., 2010. The long and short (of) quality ladders. Rev. Econom. Stud. 77, 1450–1476.

Klenow, Peter J., Rodríguez-Clare, Andr'es, 1997. The neoclassical revival in growth economics: Has it gone too far? NBER Macroeconom. Annu. 12, 73–103.

Kratz, Marie, Resnick, Sidney I., 1996. The QQ-estimator and heavy tails. Stoch. Models 12 (4), 699–724.

Krugman, Paul, 1980. Scale economies, product differentiation, and the pattern of trade. Amer. Econ. Rev. 70 (5), 950–959.

Levchenko, Andrei A., Zhang, Jing, 2016. The evolution of comparative advantage: Measurement and welfare implications. J. Monetary Econ. 78, 96–111.

Manova, Kalina, Zhang, Zhiwei, 2012. Export prices across firms and destinations. Q. J. Econ. 127, 379–436.

Mayer, Thierry, Melitz, Marc, Ottaviano, Gianmarco I.P., 2014. Market size, competition, and the product mix of exporters. Amer. Econ. Rev. 104 (2), 495–536.

Melitz, Marc J., 2003. The impact of trade on intra-industry reallocations and aggregate industry productivity. Econometrica 71, 1695–1725.

Melitz, Marc J., Redding, Stephen J., 2014. Heterogeneous firms and trade. In: Helpman, E., Gopinath, G., Rogoff, K. (Eds.), Handbook of International Economics. Vol. 4, Elsevier, North Holland, Amsterdam, pp. 1–54, Chapter 1.

Nakamura, Alice, Erwin Diewert, W., Greenlees, John S., Nakamura, Leonard I., Reinsdorf, Marshall B., 2015. Sourcing substitution and related price index biases. In: Houseman, Susan N., Mandel, Michael (Eds.), Measuring Globalization: Better Trade Statistics for Better Policy. In: Biases to Price, Output, and Productivity Statistics from Trade W.E., Vol. 1, Upjohn Institute for Employment Research, pp. 21–88.

Redding, Stephen J., Weinstein, David E., 2019. Aggregation and the gravity equation. Am. Econ. Rev. Pap. Proc. 109, 450–455.

Redding, Stephen J., Weinstein, David E., 2020. Measuring aggregate price indexes with taste shocks: Theory and evidence for CES preferences. Q. J. Econ. 135 (1), 503–560.

Redding, Stephen J., Weinstein, David E., 2023. Aggregation and Estimation of Constant Elasticity of Substitution (CES) Preferences. Princeton University, mimeograph.

Roberts, Mark J., Fan, Xiaoyan, Daniel, Xu, Shengxing, Zhang, 2018. The role of firm factors in demand, cost and export market selection for Chinese footwear producers. Rev. Econom. Stud. 85 (4), 2429–2461.

Schott, Peter K., 2004. Across-product versus within-product specialization in international trade. Q. J. Econ. 119, 647–678.

Sutton, John, 1991. Sunk Costs and Market Structure: Price Competition, Advertising, and the Evolution of Concentration. MIT Press, Cambridge MA.

Sutton, John, Trefler, Daniel, 2016. Capabilities, wealth, and trade. J. Polit. Econ. 124 (3), 826–878.