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How do endowments determine trade? quantifying the output mix, factor price, and skill-biased technology channels☆

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ABSTRACT

Differences in how countries absorb endowments of skilled and unskilled labour can be decomposed into (a) differences in the skewness of output mix towards skill-intensive industries and (b) differences in the skill intensity of each industry. The latter can be decomposed into contributions from cross-country differences in ($2a$) relative wages and ($2b$) skill-biased factor-augmenting technologies. To investigate the relative importance of each, we develop a multi-sector Eaton-Kortum model featuring skilled/unskilled labour and factor-augmenting international technology differences. The model is calibrated to WIOD data for 39 countries in 2006. Using a model-based decomposition, we show that the skill-intensity mechanism is much more important than output-mix. Further, differences in skill intensities across countries are explained in similar proportions by the relative-wage mechanism and the technology mechanism. Our results have immediate implications for the impact of endowments and skill-biased technology on output mix, trade in goods, and international differences in skill premia.

1. Introduction

Two major themes dominate the vast literature on how endowments affect international trade and domestic wages. Stated as decompositions, these themes are:

1. Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (a) differences in the skewness of output mix towards skill-intensive industries and (b) differences in the skill intensity of each industry.
2. Within each industry, cross-country differences in skill intensities can be decomposed into contributions from cross-country differences in (a) relative wages and (b) skill-biased, factor-augmenting technology.

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Many questions in the trade literature are fundamentally about the relative importance of the terms in these two decompositions. Most obviously, the impact of endowments on goods trade is likely big when 1*a* is large relative to 1*b* (e.g., Romalis, 2004; Chor, 2010) and the effect of exogenous changes in factor supplies on wages can be muted by these output-mix responses as well e.g., Burstein et al. (2020). The wage impacts of migration-induced endowment shifts can also be offset by the skill upgrading of 2*b* e.g., Gandal et al. (2004) and Dustmann and Glitz (2015). Trefler (1993, 1995) and Davis and Weinstein (2001) offer competing views as to whether the failure of the Heckscher-Ohlin-Vanek factor content prediction is due to departures from factor price equalization (2*a*), factor-augmenting international technology differences (2*b*), or trade costs.

Despite the well-known importance of these two decompositions and the many excellent country-level studies of them that we review below, an important addition to our stock of knowledge would be a cross-country study of the decompositions within a unified framework. Such an exercise faces two challenges. First, there are many other primitives (e.g. technology, preferences, trade costs, and other countries' endowments) that may change as countries accumulate factors of production. We therefore cannot use a data-based decomposition to assess the causal effect of changes in endowments on output mix and skill intensities. Therefore we use a full general equilibrium model to assess how an exogenous change in endowments is absorbed. To do this, we set up a multi-factor, multi-sector (Eaton and Kortum, 2002) model featuring the interindustry linkages of Caliendo and Parro (2015) and CES substitution possibilities between skilled and unskilled labour as in Parro (2013) and Burstein and Vogel (2017). Second, while there are various ways of estimating factor-augmenting international technology differences (Caselli and Coleman, 2006; Trefler, 1993; Malmberg, 2017), none of these is consistent with our model.[1] We therefore develop a new method of estimating factor-augmenting international technology differences. We calibrate the model using WIOD data (Timmer et al., 2015) for 39 countries and 23 industries in 2006. Our core results are also repeated for 1995. The model provides a unified framework for our two decompositions.

Having calibrated our model we turn to our first decomposition. In the 'between' and 'within' language of decompositions, we use the quantitative model to trace out the impact of a change in endowments on (1*a*) between-industry output mixes and (1*b*) within-industry skill intensities. Specifically, we consider the following thought experiment: If we reduce a country's endowments-based comparative advantage by altering its endowments, what share of these endowment changes would be absorbed by between-industry shifts in output versus within-industry shifts in skill intensities? In a standard Heckscher-Ohlin world under factor price equalization, such an exercise would imply that 1*a* accounts for 100% of the decomposition. In a single-sector model, that share would obviously be 0%. We find that for all countries, output mix plays a small role in absorbing changes in endowments: On average, output mix accounts for only 2.3% of the decomposition and skill intensity accounts for the remaining 97.7%. In short, the output-mix channel is only a small part of the adjustment mechanism. In our literature review, we document that this stark result appears in many (though not all) individual-country studies on the effects of migration.

Does our result conflict with existing evidence of Rybczynski and Heckscher-Ohlin effects e.g., Baldwin (1971), Romalis (2004), Chor (2010), and Morrow (2010)? The answer is no. When we run regressions based on Romalis (2004) using our data, we replicate his findings. This points to the distinction between (*i*) observing that output-mix changes have the *direction* predicted by our theories and (*ii*) finding that these changes are important in *magnitude* for how countries absorb their endowments.

We next turn to our second decomposition, decomposing cross-country skill-intensity differences into contributions from (2*a*) cross-country wage differences and (2*b*) factor-augmenting international technology differences. To show this in a quantitative model we proceed as follows. In any country *i*, the skill intensity of an industry – meaning the requirement of skilled labour relative to unskilled labour – is a function among other things of the relative wage and the skill bias of factor-augmenting technology (λ_i^V). We consider the thought experiment of 'switching off' the factor-augmenting technology parameters by setting the λ_i^V to unity in all countries. Just as in the case of our endowments thought experiment there will be impacts on output mix and, via general-equilibrium wage changes, impacts on skill intensities. The latter is our 2*a*. In addition, there is an effect not present with endowment changes, namely, the direct impacts of skill-biased technology on skill intensities. This is our 2*b*. We find that the output-mix effect is very small and that 2*a* and 2*b* are of comparable size.[2] In addition to being of intrinsic interest to the migration and Heckscher-Ohlin-Vanek literatures noted above, this ties our results into the literature on induced technical change e.g., Acemoglu (1998) and Burstein and Vogel (2017).

While the λ_i^V are important for our decompositions, it is good to establish their importance more generally. To this end, we compare the role of the λ_i^V to the role of the Ricardian technology parameters, parameters that have been documented as important elsewhere e.g., Costinot et al. (2012). Specifically, we compare the effects of switching off the λ_i^V with the effects of switching off the Ricardian technology parameters on equilibrium unit input requirements.[3] Here we look not just at skill intensities, which should not be much affected by Ricardian considerations, but at the levels of factor demands and wages. When we do this, we find that the two sets of technology parameters have comparable counterfactual power. Hence, our emphasis on factor-augmenting technologies is appropriate in terms of being quantitatively important.

Our decomposition of skill intensities into wages and technology bears directly on an older debate about the failure of the Heckscher-Ohlin-Vanek factor content of trade prediction. While there are many explanations for its failure, two prominent

[1] E.g., Caselli and Coleman (2006) use an aggregate production function and Malmberg has no intermediate inputs.

[2] That 2*a* and 2*b* are of comparable size is a consequence of a small output-mix effect. If endowments do not change then the labour market clearing conditions imply that our three effects (output-mix, 2*a* and 2*b*) must sum to zero. If in addition the output-mix is close to zero then 2*a* and 2*b* must sum to close to zero. That is, they must be of equal size and opposite sign.

[3] When switching off Ricardian technology parameters, we see substantial output reallocation.

ones are departures from factor price equalization and factor-augmenting productivity differences.[4] Davis and Weinstein (2001) point to the failure of factor price equalization and arrive at this conclusion by showing that international differences in factor intensities are driven by international differences in factor prices. In contrast, Trefler (1993) points to international differences in factor-augmenting technology and arrives at this conclusion by considering productivity-adjusted skill intensities. Our decomposition of skill intensities shows that factor prices and factor-augmenting technology are *both* important. It follows that Davis and Weinstein (2001) and Trefler (1993) were both right, but that each had only a partial picture of the problem. We are able to show this because of advances in quantitative modelling which allow us to endogenize wages, an advance that was not available to these researchers. We close by asking whether taking these two factors into account is enough to rescue the Vanek equation. The answer is no: Even after taking these into account, there is still missing trade that we then unpack using our quantitative model.

Our approach is subject to a few limitations. First and foremost, we do not endogenize factor-augmenting technology. This cannot be over-emphasized. Second, the WIOD data we use is very aggregated (23 sectors in the economy). Therefore, some between-industry output reallocation is not captured by the data e.g., a shift within apparel from sewing to cutting. This likely contributes to why only 2.3% of endowment absorption is due to industry re-allocation. However, if with finer data this number doubled or tripled, it would make little difference to our headline conclusion that absorption is largely driven by within-industry differences in skill intensities. Third, we do not estimate the elasticity of substitution between skilled and unskilled labour (σ). There are two views on this. On the one hand, it is a defect not to be using an internally consistent measure of σ. On the other hand, doing so would likely overfit the data, thus limiting the value of the exercise. Given the availability of high-quality estimates of σ (e.g., Acemoglu and Autor, 2011), we prefer not to estimate it, though others may reasonably have a different view.[5]

1.1. Literature review

Our paper is most closely related to research which attaches skilled and unskilled labour to a multi-sector Eaton-Kortum model. See especially Parro (2013), Caron et al. (2014), Burstein et al. (2013), and Burstein and Vogel (2017). These papers are largely concerned with the impact of falling trade costs on the skill premium. In contrast, our interest in the skill premium is not as an outcome to be explained but as one of several channels through which economies adjust to their endowments.[6]

A large literature on the impact of migration on US states and cities finds that output-mix adjustments play only a small role in absorbing changes in factor supply. Card and Lewis (2007) find that in response to unskilled Mexican migration, most cities did not experience either output-mix or relative wage changes. They did experience skill-intensity changes, but the authors do not investigate whether or not this is due to skill-biased technology adoption. Lewis (2004) examines the impact of the Mariel boat lift and Gandal et al. (2004) examine the impact of Russian immigration to Israel. Both find that the immigration did not cause changes in output mix, but did accompany differential adoption of factor-biased technologies. Two studies that exploit immigration impacts on US states and commuting zones are Hanson and Slaughter (2002) and Burstein et al. (2020). Both find evidence of substantial output-mix effects, especially for tradable industries and occupations, respectively. The latter also find that price movements are important for nontradable sectors. In our cross-country setting–as opposed to the above cross-state or cross-commuting zone setting–we expect very low levels of mobility/migration and very weak pressures for factor price equalization, so we expect our results to have weaker output-mix effects.

Other parts of the international trade literature place less of an emphasis on the effect of changes in factor supply *per se*, and focus more on how output composition changes in response to trade liberalization. While factor endowment based trade theories predict strong reallocations across sectors following trade reforms, Goldberg and Pavcnik (2007) document little evidence in support of such reallocation.[7] Parro (2013) uses a structural model to estimate the effect of a reduction in bilateral trade costs on the skill premium using a canonical factor endowments model and finds that the magnitudes of the resulting changes are very close to zero, which reflects a small amount of increased specialization across sectors.

Finally, our paper is related to another literature on structural estimation of the the world matrix of direct requirements of primary factors ($\boldsymbol{D}$) and the world input-output matrix of direct requirements of intermediate inputs ($\boldsymbol{B}$). The existing

[4] A full list of supply-side explanations includes Hicks-neutral international productivity differences (e.g., Trefler, 1995; Debaere, 2003), Ricardian productivity differences (e.g., Marshall, 2012, but not Nishioka, 2012), factor-augmenting productivity differences (e.g., Trefler, 1993), factor prices (e.g., Fadinger, 2011) and trade costs (e.g., Staiger et al., 1987). Davis and Weinstein (2001) are unique in ambitiously considering all of these determinants, excluding factor-augmenting productivity differences.

[5] We could easily estimate σ using GMM. While σ is not identified in the cross-section (see Section 2 or Diamond et al., 1978), we could follow Katz and Murphy (1992) in using annual data and adding a time trend to the evolution of the λ_i^V technology parameters. Then σ is over-identified and can be estimated using GMM.

[6] Parro (2013) examines the impact of trade in capital goods on the skill premium. He considers a third factor (capital) which complements skilled labour and thus influences the skill premium. He provides a model-based decomposition of the skill premium and finds that trade in capital goods has important impacts on inequality. Burstein et al. (2013) is closely related to Parro (2013), but of less relevance here given our interest in endowments-based comparative advantage because they assume that factor intensities are the same across industries. Burstein and Vogel (2017) introduce trade-induced directed technical change. They allow for within-industry firm heterogeneity in which more productive firms use more skill-intensive techniques. They then examine the impact of trade and technical change on the skill premium. Again, this is not our primary focus. Importantly, they allow the skill-bias of technology to adjust endogenously due to selection effects, whereas we treat technology as exogenous. Our evidence strongly supports their research direction. Caron et al. (2014) is primarily concerned with non-homothetic preferences as a source of comparative advantage.

[7] Specifically, they cite studies by Revenga (1997), Hanson and Harrison (1999), and Feliciano (2001) for Mexico; by Attanasio et al. (2004) for Colombia; by Currie and Harrison (1997) for Morocco; by Topalova (2010) for India; and by Wacziarg and Wallack (2004) in a cross-country comparison.

Heckscher-Ohlin-Vanek (HOV) literature has not taken a structural approach to estimating $\boldsymbol{D}$ and $\boldsymbol{B}$: Trefler (1995) estimates $\boldsymbol{D}$, Davis and Weinstein (2001) estimate $\boldsymbol{D}(\boldsymbol{I} - \boldsymbol{B})^{-1}$, and neither uses prices for this estimation. More recently, Caliendo et al. (2017) and Antràs and de Gortari (2017) structurally estimate $\boldsymbol{B}$ using prices and taking into account price endogeneity. We structurally estimate $\boldsymbol{D}$ and $\boldsymbol{B}$ as functions of endogenous prices and productivity parameters.

1.2. Outline

Section 2 begins by discussing a fundamental identification problem encountered when one tries to identify factor-augmenting productivity using data on skill intensity and skill premia. Section 3 presents our model. Section 4 describes our data and strategy for calibrating the parameters of the model. Section 5 presents evidence from model-based counterfactual for the first of our decompositions: how countries absorb differences in endowments. Section 6 presents model-based evidence for the second of our decompositions: how skill intensities decompose into wages and technology. Section 7 shows that our small output effects are fully consistent with recent reduced form evidence assessing the Heckscher-Ohlin model. Section 8 briefly links our results to the literature on directed technical change. Section 9 discusses the implications of our results for tests of the fit of the Heckscher-Ohlin-Vanek equation. Section 10 concludes.

2. Identification

Disentangling substitution effects (mechanism *2a*) from factor-augmenting international technology differences (mechanism *2b*) raises an identification issue documented by Diamond et al. (1978), but ignored in the trade-and-endowments literature. Consider the following cost function for industry g in country i:

$$c^V_{gi} = \left(\sum_f \alpha_{fg} \left(w_{fi}/\lambda^V_{fi} \right)^{1-\sigma} \right)^{1/(1-\sigma)} \tag{1}$$

where w_{fi} is the price of factor f in country i, λ^V_{fi} is a factor-augmenting technology parameter, and the non-negative α_{fg} parameters control factor intensities. Let $d_{fgi} = \partial c^V_{gi}/\partial w_{fi}$ be a unit input requirement. As is well known, the d_{fgi} satisfy

$$\frac{d_{Sgi}/d_{Sgus}}{d_{Ugi}/d_{Ugus}} = \left(\frac{w_{Si}/w_{Sus}}{w_{Ui}/w_{Uus}} \right)^{-\sigma} \left(\frac{\lambda^V_{Si}}{\lambda^V_{Ui}} \right)^{\sigma-1} \tag{2}$$

where $f = S, U$ indexes skilled and unskilled labour, $i =$ us indexes the United States, and we have normalized productivities using $\lambda^V_{fus} = 1$. This equation helps us explain the identification issue.

Suppose we only have cross-sectional data as, for example, in Trefler (1993) and Davis and Weinstein (2001). In particular, suppose that we only observe data on (d_{Ugi}, d_{Sgi}) and (w_{Ui}, w_{Si}) for two countries $i = 1, 2$. Fig. 1 plots an isoquant in (U, S) space. Points correspond to pairs (d_{Ugi}, d_{Sgi}) and slopes to $-w_{Ui}/w_{Si}$. Now consider the problem of disentangling whether cross-country variation in unit requirements is driven by substitution effects (mechanism *2a*) or factor-augmenting international technology differences (mechanism *2b*). One approach is to make the identifying assumption that technologies are internationally identical and then fit the data by choosing an isoquant curvature parameter σ to hit the two data points in panel (*A*). Another approach is to pin down σ using an external estimate and then to choose international technology differences $\lambda^V_i \equiv \lambda^V_{Si}/\lambda^V_{Ui}$ that generate the tangencies in panel (*B*). In between there are countless other approaches involving mixtures of curvature and international technology differences. Each approach can rationalize the data, that is, σ and $\lambda^V_{Si}/\lambda^V_{Ui}$ are not separately identified.

Trefler (1993) and Davis and Weinstein (2001) make claims about the importance of factor augmentation and/or substitution effects. How do they obtain identification? Trefler (1993)'s identification assumption is productivity-adjusted factor price equalization (PFPE) i.e., $w_{fi}/\lambda^V_{fi} = w_{fus}$. Then the right side of Eq. (2) reduces to $\lambda^V_{Si}/\lambda^V_{Ui}$ and this is identified by the d_{fgi} data on the left side of (2). Identification is illustrated in panel (*C*) where the axes are productivity-adjusted factor inputs so that international differences in technology and factor prices disappear. Since all data for an industry are on a single point, Trefler cannot examine substitution effects along an isoquant (mechanism *2a*).

Davis and Weinstein (2001)'s identification assumption is that there are only Hicks-neutral productivity differences so that $\lambda^V_{Si}/\lambda^V_{Ui} = 1$ i.e., mechanism (*2b*) disappears by assumption. Then the right side of Eq. (2) becomes $(w_{fi}/w_{fus})^{-\sigma}$, data on the d_{fgi} and w_{fi} identify σ, and they can analyze the role of the failure of factor price equalization.[8]

Summarizing, the presence of cross-country differences in relative prices *and* factor-augmenting technology creates an identification issue that has been ignored in the trade-and-endowments literature and whose resolution affects conclusions about the relative importance of mechanisms (*2a*) and (*2b*). In this paper, we use the technique illustrated in Fig. 1b. We appeal to Katz

[8] This discussion should not be viewed as a summary of Davis and Weinstein (2001). Among other things, they only analyze mechanism (*2a*), not (*2b*). Also note that they do not use data on w_{fi}, which raises an identification issue that pops up elsewhere in the literature. They implicitly solve the identification problem by proxying relative wages with relative endowments in their P4 and P5 specifications. In the spirit of Katz and Murphy (1992), this is related to a regression of log relative wages on log relative endowments and the coefficient is the inverse of σ. Romalis (2004) and Chor (2010) follow a similar strategy. Interestingly, we will provide some general equilibrium empirical support for this reduced-form approach in Section 5.

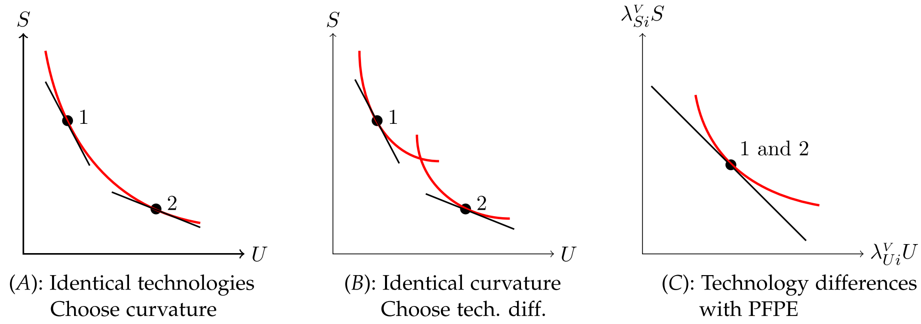

Fig. 1. Identification.

and Murphy (1992) and Acemoglu and Autor (2011) who use time series U.S. data to identify σ in the presence of linearly trending factor-augmenting (skill-biased) technical change. Acemoglu and Autor (2011) note that most researchers estimate σ to be between 1.4 and 2, and their own research puts σ between 1.6 to 1.8 (see pg. 1107–1109). We therefore use the midrange of 1.7. Section 5 shows that our results change in only small but predictable ways when using values of σ=1.3 or 2.

3. A quantitative model

This section describes our quantitative general equilubrium model. We slightly extend the Caliendo and Parro (2015) model by adding skilled and unskilled labour. This framework will allow us to examine in general equilibrium the importance of the mechanisms described above in how countries absorb factor endowments. To get quickly to what is new we assume the reader is familiar with the Eaton and Kortum (2002) model and start with price determination as this will reduce notation.

3.1. Product prices in equilibrium

Let $i, j = 1, \ldots, N$ index countries, $g, h = 1, \ldots, G$ index goods or industries, and $\omega_g \in [0, 1]$ index varieties of good g. A variety is potentially produced by many firms that sell into perfectly competitive international markets. Unit costs of producing ω_g in country i are given by $c_{gi}/z_{gi}(\omega_g)$ where $z_{gi}(\omega_g)$ is a variety-specific productivity drawn from a Fréchet distribution with location parameter 1 and shape parameter θ_g. c_{gi} is described in detail below. There are also iceberg trade costs: $\tau_{gi,j}$ is the cost of shipping any variety of g from country i to country j or, more succinctly, the cost of shipping (g, i) to j. We assume that the $\tau_{gi,j}$ satisfy the triangle inequality. As in Eaton and Kortum (2002) and Caliendo and Parro (2015), the price of ω_g in country j is therefore

$$p_{gj}(\omega_g) = min_i \frac{c_{gi}\tau_{gi,j}}{z_{gi}(\omega_g)}. \tag{3}$$

3.2. Households

Household preferences in country i are given by:

$$U_i = \prod_{g=1}^{G} \left\{ \left(\int_0^1 x_{gi}(\omega_g)^{\frac{\rho_g - 1}{\rho_g}} d\omega_g \right)^{\frac{\rho_g}{\rho_g - 1}} \right\}^{\gamma^U_{gi}} \tag{4}$$

where $x_{gi}(\omega_g)$ is an amount of ω_g consumed in country i, $\rho_g > 1$ is the consumption elasticity of substitution within an industry, and the non-negative Cobb-Douglas share parameters satisfy $\sum_g \gamma^U_{gi} = 1$. Total household expenditure is given by $\sum_g \left(\int p_{gi}(\omega_g) x_{gi}(\omega_g) d\omega_g \right)$. Household income is given by total payments to its endowments of skilled and unskilled labour that the household supplies inelastically. Household expenditure may differ from its income because of transfers/deficits that we discuss below.

3.3. Goods producers

The technology for producing goods is exactly as in Caliendo and Parro (2015) but with multiple primary factors. Output $q_{gi}(\omega_g)$ of variety ω_g in country i is produced using:

1. A bundle of primary factors. For industry g in country i, the cost of the bundle is c^V_{gi} as in Eq. (1).

2. Bundles of intermediate inputs $h = 1, \ldots, G$ where the hth bundle is CES with elasticity of substitution ρ_h. The cost of bundle h in country i is $P_{hi} \equiv \left[\int_0^1 [p_{hi}(\omega_h)]^{1-\rho_h} d\omega_h\right]^{1/(1-\rho_h)}$.

The upper-tier production function is Cobb-Douglas so that the resulting unit cost function for $q_{gi}(\omega_g)$ is $c_{gi}/z_{gi}(\omega_g)$ and

$$c_{gi} = \frac{\kappa_{gi}}{\lambda^R_{gi}} \left\{ \left[\sum_f \alpha_{fg} \left(w_{fi}/\lambda^V_{fi} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \right\}^{\gamma^V_{gi}} \prod_{h=1}^{G} (P_{hi})^{\gamma^I_{h,gi}} . \tag{5}$$

The term in braces is c^V_{gi} from Eq. (1). γ^V_{gi} is the share of primary inputs in costs and $\gamma^I_{h,gi}$ is the share of intermediate input bundle h in costs. V and I superscripts denote Value added and Intermediates, respectively. Cost shares vary by good g and location of production i so that all Cobb-Douglas parameters have (g, i) subscripts. We impose constant returns to scale: $\gamma^V_{gi} + \sum_{h=1}^{G} \gamma^I_{h,gi} = 1$.[9] The remaining parameters capture productivity. As before, λ^V_{fi} is the efficiency of factor f in country i and captures factor-augmenting international technology differences. λ^R_{gi} is the efficiency of industry g in country i and captures Ricardian comparative advantage. Exploiting standard Fréchet properties:

$$P_{gi} = \kappa_g \left[\sum_{j=1}^{N} \left(c_{gj} \tau_{gj,i} \right)^{-\theta_g} \right]^{-1/\theta_g} , \tag{6}$$

where $\kappa_g \equiv \Gamma((1+\theta_g-\rho_g)/\theta_g)^{1/(1-\rho_g)}$ and we assume that $\theta_g > \rho_g - 1$. Let $\pi_{gi,j}$ be the share of g that j sources from i. Again, exploiting standard Fréchet properties,

$$\pi_{gi,j} = \frac{\left(c_{gi} \tau_{gi,j} \right)^{-\theta_g}}{\sum_{i'=1}^{N} \left(c_{gi'} \tau_{gi',j} \right)^{-\theta_g}} . \tag{7}$$

The richness of the model means there are a lot of parameters. Table 1 reviews them.

3.4. Equilibrium

Let Q_{gi} be the value of (g, i) output summed across varieties. Let D_j be country j's trade deficit. We follow Caliendo and Parro (2015) in treating the D_j as exogenous. Globally, trade is balanced so that $\sum_j D_j = 0$. This allows us to write down an expression for country j's expenditures on good g produced by country i:

$$E_{gi,j} \equiv \pi_{gi,j} \sum_{h=1}^{G} \gamma^I_{g,hj} Q_{hj} + \pi_{gi,j} \gamma^U_{gj} \left(\sum_{h=1}^{G} \gamma^V_{hj} Q_{hj} + D_j \right) . \tag{8}$$

This equation is notationally demanding and an understanding of it is not necessary for the reader to work through the rest of the model. Therefore, a detailed explanation of it is relegated to Appendix A.[10] We can now state the key equilibrium conditions.

Goods market clearing: Setting sales of (g, i) equal to expenditures on (g, i) yields

$$Q_{gi} = \sum_{j=1}^{N} E_{gi,j}. \tag{9}$$

Factor market clearing: Each country i is endowed with an inelastic supply of primary factors V_{fi}. Factor demand at the industry level per dollar of sales is given by

$$d_{fgi} = \left(\gamma^V_{gi}/\lambda^V_{fi} \right) \left[\alpha_{fg} \left(w_{fi}/\lambda^V_{fi} \right)^{-\sigma} \right] \Big/ \left[\sum_{f'} \alpha_{f'g} \left(w_{f'i}/\lambda^V_{f'i} \right)^{1-\sigma} \right]. \tag{10}$$

[9] $\kappa_{gi} \equiv (\gamma^V_{gi})^{-\gamma^V_{gi}} \prod_h (\gamma^I_{h,gi})^{-\gamma^I_{h,gi}}$.

[10] For a reader who needs at least a rough understanding of Eq. (8) we note the following. The first term is expenditures by producers in country j on intermediate input g sourced from country i. The second term is expenditures by consumers in country j on final good g sourced from country i. The term in parentheses is country j's spending power, which is the sum of income earned by j's primary factors ($\gamma^V_{hj} Q_{hj}$ is value added generated by producing good h) and a transfer D_j from the rest of the world.

Table 1
Notation.

Indexes	
g, h	goods (usually g uses h as an input)
i, j	countries (usually i exports to j)
f	factors ($f = S, U$ for skilled and unskilled labour)
Share parameters	
γ^V_{gi}	*V*alue added as a share of total costs for g produced in i
$\gamma^I_{h,gi}$	*I*ntermediate input h as a share of total costs for g produced in i
γ^U_{gi}	consumption of good g as a share of country i's total consumption (U for *U*tility)
	Note: $\gamma^V_{gi} + \sum_h \gamma^I_{h,gi} = 1$ and $\sum_g \gamma^U_{gi} = 1$
α_{fg}	factor intensity parameter for factor f used to produce good g
κ_g, κ_{gi}	Functions of γ^V_{gi}, γ^I_{gi}, θ_g and ρ_g. See Section 3.3
Key technology parameters	
λ^R_{gi}	*R*icardian productivity when producing good g in country i
λ^V_{fi}	factor-augmenting productivity of factor f in country i (V for value added)
Elasticities	
σ	elasticity of substitution between skilled and unskilled labour
θ_g	Fréchet shape parameter for good g
ρ_g	elasticity of substitution between varieties of good g
Flows from country i to country j	
$\tau_{gi,j}$	iceberg cost of shipping good g from country i to country j
$\pi_{gi,j}$	share of g that country j sources from country i, $\sum_i \pi_{gi,j} = 1$
$M_{gi,j}$	country j's imports of good g from country i
X_{gi}	country i's total exports of good g
Good g produced in Country i	
c_{gi}	common input cost of producing one unit of good g in country i
c^V_{gi}	value added in one unit of good g produced in country i
$d_{fgi}, \widetilde{d}_{fgi}$	factor f needed to produce one dollar of good g in country i. ($\widetilde{d}_{fgi}$ when measured in productivity-adjusted units)
$b_{gi,hj}$	value of intermediate input g from country i needed to produce one dollar of h in j
Factors	
$V_{fi}, \widetilde{V}_{fi}$	country i's endowment of factor f. ($\widetilde{V}_{fi}$ when measured in productivity-adjusted units)
$w_{fi}, \widetilde{w}_{fi}$	wages of factor f in country i. ($\widetilde{w}_{fi}$ when measured in productivity-adjusted units)

The proof appears in Appendix B. Factor demands are usually defined per unit of output and this is how we defined d_{fgi} earlier. We now define it per dollar of output in order to seamlessly match the WIOD data.[11] Hence $d_{fgi}Q_{gi}$ is the amount of factor f employed producing (g, i) and factor market clearing is

$$\sum_{g=1}^{G} d_{fgi} Q_{gi} = V_{fi}. \tag{11}$$

Equilibrium: Equilibrium is a set of prices w_{fi} and $p_{gi}(\omega_g)$ which clear factor markets domestically (Eqs. (10) and (11)) and clear product markets internationally (Eq. (9)) subject to producers minimizing costs and consumers maximizing utility. In Eqs. (9) and (11), the variables (P_{gi}, c_{gi}, π_{gij}, $E_{gi,j}$, Q_{gi}) satisfy Eqs. (5)–(8).

4. Data and calibration

Unless otherwise noted, all data come from the World Input-Output Database (WIOD) as assembled by Timmer et al. (2015). The database has the advantage of providing information on the full world input-output matrix and satisfying all world input-output identities. Our data cover 39 developed and developing countries and 23 industries in the year 2006 although we also

[11] This redefinition does not affect anything we wrote above because we have only worked with ratios d_{Sgi}/d_{Ugi} and in ratios the scaling of d_{fgi} (per unit or per dollar) cancels out.

present results for 1995.[12] WIOD includes data on output, consumption, trade, and purchases of intermediate inputs. It also includes labour by educational attainment: Skilled workers possess some tertiary education while unskilled workers are the remainder of the labour force. For each type of labour, WIOD reports hours worked and compensation by industry and country. We measure wages as compensation divided by hours and employment as hours worked. The direct input requirement d_{fgi} is hours worked divided by sales.

The parameters to be calibrated are listed in Table 1. The Cobb-Douglas share parameters γ_{gi}^U, γ_{gi}^V and $\gamma_{h,gi}^I$ are taken from the WIOD share data. As emphasized by de Gortari (2019), these fit the consumption and production share data perfectly. α_{Sg} and $\alpha_{Ug}=1-\alpha_{Sg}$ are pinned down by Eq. (10) for the United States.[13] We do not let the θ_g vary by industry as this would introduce yet another source of comparative advantage into our model (Fieler, 2011; Caron et al., 2014). We drop the g subscript on θ_g and set θ=5.03, which is its meta study median value across 32 papers that estimate θ using tariff and/or freight rate data (Head and Mayer, 2014, table 5). As discussed at the end of Section 2, we start with a value of $\sigma=1.70$.[14]

There are two features of our model that provide natural starting points for estimating the remaining parameters of the model. The first is substitution between skilled and unskilled labour, as controlled by σ, which appears in Eq. (10). We use (10) as the basis for estimating the λ_{fi}^V. The second is productivity heterogeneity, controlled by θ, and this appears in the gravity Eq. (7) which we use to estimate the $\tau_{gi,j}$ and λ_{gi}^R.

4.1. The gravity equation and calibration of the $\tau_{gi,j}$ and λ_{gi}^R

We build on Waugh (2010) and Levchenko and Zhang (2012). From Eq. (7),

$$\ln \pi_{gi,j}/\pi_{gj,j} = -\theta \ln\left(c_{gi}\right) + \theta \ln\left(c_{gj}\right) - \theta \ln\left(\tau_{gi,j}\right) \tag{12}$$

where we set $\tau_{gj,j}=1$. We parameterize $\theta \ln\left(\tau_{gi,j}\right)$ as $\psi_g x_{ij}$ where ψ_g is a vector of regression coefficients and x_{ij} is a vector of standard covariates. We then estimate the gravity equation

$$\ln \pi_{gi,j}/\pi_{gj,j} = \delta_{gi} - \delta_{gj} - \psi_g x_{ij} + \varepsilon_{gi,j} \tag{13}$$

where the δ_{gi} are exporter-industry fixed effects. (When $i=j$ the 'exporter' is the domestic producer.) $\varepsilon_{gi,j}$ captures unmeasured trade costs and model misspecification. Estimating this equation separately for each industry g generates estimates of $\theta \ln \tau_{gi,j} = \hat{\psi}_g x_{ij}$ and hence of the $\tau_{gi,j}$.[15]

Levchenko and Zhang (2012) use the estimated δ_{gi} to recover the $c_{gi}/c_{g,\mathrm{us}}$ and show that when the γ_{gi}^V and $\gamma_{h,gi}^I$ are independent of i, the $c_{gi}/c_{g,\mathrm{us}}$ can be used to recover the Ricardian productivity parameters $\lambda_{gi}^R/\lambda_{g,\mathrm{us}}^R$. In Appendix D.1 we extend their method to the case where the γ_{gi}^V and $\gamma_{h,gi}^I$ depend on i. Online Appendix Table B1 displays a transformation of our measures of $\lambda_{gi}^R/\lambda_{g,\mathrm{US}}^R$.

4.2. The factor demand equation and calibration of the λ_{fi}^V

Manipulating Eq. (10) to obtain Eq. (2) and introducing an error to allow for functional-form misspecification, we obtain

$$d_{gi} = \beta_i + \nu_{gi} \quad \text{where} \quad d_{gi} \equiv \frac{d_{Sgi}/d_{Sg,\mathrm{us}}}{d_{Ugi}/d_{Ug,\mathrm{us}}} \quad \text{and} \quad \beta_i \equiv \left(\frac{w_{Si}/w_{S\mathrm{us}}}{w_{Ui}/w_{U\mathrm{us}}}\right)^{-\sigma}\left(\frac{\lambda_{Si}^V}{\lambda_{Ui}^V}\right)^{\sigma-1}. \tag{14}$$

We estimate $d_{gi}=\beta_i+\nu_{gi}$ by regressing d_{gi} on country dummies. The estimated dummies are estimates of the β_i. The regression pools across industries and countries and uses weighted least squares with weights ω_{gi}^L that are industry g's share of country i's total employment ($\sum_g \omega_{gi}^L=1$). This places greater weight on industries that are more important for the country and less weight on small

[12] The 2013 vintage of WIOD covers 35 sectors. We aggregate up to 23 industries to make results comparable to Davis and Weinstein (2001) and Trefler (1993, 1995). No industries are dropped. See Appendix C for details. We use 2006 because it is the most recent year before the Great Recession and the subsequent trade collapse and also because it is the year used by Burstein and Vogel (2017).

[13] $\alpha_{fg} = w_{f\mathrm{us}}^{\sigma} V_{fg\mathrm{us}} / (\sum_{f'} w_{f'\mathrm{us}}^{\sigma} V_{f'g\mathrm{us}})$.

[14] As is well known the ρ_g play almost no role in Eaton-Kortum style models, including ours. We thus follow Levchenko and Zhang (2012) in setting them to a common value of 4. This satisfies the requirement $\theta > \rho - 1$.

[15] x_{ij} consists of the following bilateral dummy variables: common border; common language; colonial relationship; common customs union; preferential trade area; and, following Eaton and Kortum (2002), dummies for each of the distance intervals [0, 350], (350, 750], (750, 1500], (1500, 3000], (3000, 6000], and >6000 miles. The coding of the customs union and preferential trade dummies is described in Appendix C. All other data are from CEPII. See http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=8 by Thierry Mayer.

industries. The resulting estimate of each β_i is just the weighted average $\hat{\beta}_i = \sum_{g=1}^{23} \omega_{gi}^L d_{gi}$. We calibrate factor-augmenting productivities using

$$\frac{\lambda_{Si}^V}{\lambda_{Ui}^V} = \left(\frac{w_{Si}/w_{Sus}}{w_{Ui}/w_{Uus}}\right)^{\frac{\sigma}{(\sigma-1)}} \hat{\beta}_i^{\frac{1}{(\sigma-1)}} = \left(\frac{w_{Si}/w_{Sus}}{w_{Ui}/w_{Uus}}\right)^{\frac{\sigma}{(\sigma-1)}} \left(\sum_g \omega_{gi}^L \frac{d_{Sgi}/d_{Sg,us}}{d_{Ugi}/d_{Ug,us}}\right)^{\frac{1}{(\sigma-1)}} . \tag{15}$$

Finally, absolute advantage depends on the product of the λ_{fi}^V and λ_{gi}^R (see Eq. (5)) so we cannot separately determine the level of each. We must normalize one or the other. Given our focus on endowments we load absolute advantage on the λ_{fi}^V and pin down their levels by normalizing the λ_{gi}^R. The normalization is described at the end of Appendix D.1. We will flag the rare instances of results that are not invariant to the choice of normalization.

4.3. Final thoughts

Having calibrated the model, we can express factor demands per dollar of output d_{fgi} as functions of factor prices and factor-augmenting technology.[16] Likewise, we can express intermediate input demands as functions of prices and technology. This is done explicitly in part 4 of lemma 2 and is accompanied by a broader discussion that appears in subsection 3 of Appendix D ("Simulation of World Input-Output Table, Trade, and Consumption"). The upshot is that we are adding to the existing Heckscher-Ohlin-Vanek (HOV) literature by taking a structural approach to estimating the direct requirements of primary factors (***D***) and the world input-output matrix of direct requirements of intermediate inputs (***B***). We are also building on a more recent literature that structurally estimate ***B*** as a function of prices (Caliendo et al., 2017; Antràs and de Gortari, 2017).

5. How do economies adjust to endowments?

We argued in the introduction that many questions in the literature on endowments, trade, and wages depend on the components of two decompositions:

1. Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (*a*) differences in the skewness of output mix towards skill-intensive industries and (*b*) differences in the skill intensity of each industry.
2. Within each industry, cross-country differences in skill intensities can be decomposed into contributions from cross-country differences in (*a*) relative wages and (*b*) skill-biased, factor-augmenting technology.

For example, the traditional factor price equalization version of Heckscher-Ohlin and Vanek (e.g., Bowen et al., 1987) assumes that all of the adjustment is through output mix. Helpman (1984) and Davis and Weinstein (2001) introduce a role for relative wages while Trefler (1993) introduces a role for factor-augmenting technology with PFPE. Although we take skill-biased technology into account, we will treat it as exogenous and will abstract from its endogenous determination in which it might both affect and be affected by trade as in Gancia and Bonfiglioli (2008) and Gancia and Zilibotti (2009).

A simple way to perform this decomposition is with data. Comparing data for 1995 and 2006, we can use the labour-market clearing condition (eq. (11)) to decompose endowment changes into changes associated with (1a) changes in output mix and (1b) changes in unit input requirements (skill intensities). We describe and report this decompositon in Online Appendix B. It leads to a very puzzling result. We might expect that as countries become more skill abundant, the wages of skilled relative to unskilled labour fall. Hence (1a) skill-intensive industries expand and (1b) skill intensities rise. Since both of these absorb rather than shed skilled labour, both must have the same sign in our 1995–2006 decomposition. Yet for more than a third of the countries in our sample, (1a) and (1b) have opposite signs. Thus, for example, as these countries become more skill abundant they either contract their skill-intensive industries or use less skill-intensive techniques.

This is not surprising given the many other changes to primitives (e.g. technology, preferences, trade costs, other countries' endowments) that were happening across countries during 1995–2006. We therefore cannot interpret a data-based decomposition as the causal effect of changes in endowments on output mix and skill intensities. Consequently, we turn to our model-based decomposition.

There are many possible ways of perturbing a country's relative endowments. We consider a change that is tightly aligned with endowments-based theories of comparative advantage: We counterfactually put each country i onto the diagonal of an Edgeworth-Bowley box in endowment space so that its relative endowments are the same as the world's relative endowments.

In summing national endowments to get world endowments we heed Leontief (1953)'s (Leontief, 1953) observation that U.S. labour is much more productive than Indian labour, making it unclear what the sum of U.S. and Indian labour means economically. We therefore follow Trefler (1993) in measuring endowments in efficiency units before summing them. To this end, define

$$\tilde{V}_{fi} = \lambda_{fi}^V V_{fi}, \quad \tilde{V}_{fw} = \sum_i \tilde{V}_{fi}, \quad \tilde{w}_{fi} = w_{fi}/\lambda_{fi}^V, \quad \tilde{d}_{fgi} = \lambda_{fi}^V d_{fgi} \tag{16}$$

[16] We can express factor demands *per unit of output* as functions of all prices and technology parameters using Eq. (19) below.

as productivity-adjusted endowments, world endowments, wages, and factor input usage, respectively.

We switch off country i's endowments-based comparative advantage by choosing $\widetilde{V}'_{fi}$ so that

$$\frac{\widetilde{V}'_{Si}}{\widetilde{V}'_{Ui}} = \frac{\widetilde{V}_{Sw}}{\widetilde{V}_{Uw}}. \tag{17}$$

That is, we put country i onto the diagonal of an Edgeworth-Bowley box in productivity-adjusted endowment space. To pin down the level of endowments we follow Costinot et al. (2012) in holding world income shares constant so as to leave absolute advantage unchanged. We do this by scaling the $\widetilde{V}'_{Si}$ and $\widetilde{V}'_{Ui}$ up or down by a common constant chosen so that equilibrium income shares are the same as in the benchmark equilibrium. This ensures that our change in endowments does not change absolute advantage.[17]

Consider how country i changes as we move it from an equilibrium in which it is on the diagonal (variables denoted with primes) to the benchmark equilibrium. For any variable x let $\Delta \ln x = \ln x - \ln x' = \ln(x/x')$. We rewrite the factor-market clearing condition in productivity-adjusted terms: $\widetilde{V}_{fi} = \sum_g \widetilde{d}_{fgi} Q_{gi}$.[18] This allows us to decompose the change in endowments into within-industry changes in $\widetilde{d}_{fi}$ and between-industry changes in Q_{gi}. Totally differentiating $\widetilde{V}_{fi} = \sum_g \widetilde{d}_{fgi} Q_{gi}$ and differencing across skilled and unskilled labour yields:

$$\underbrace{\sum_{g=1}^{G} (\theta_{Sgi} - \theta_{Ugi}) \Delta \ln Q_{gi}}_{B_i} + \underbrace{\sum_{g=1}^{G} \left(\theta_{Sgi} \Delta \ln \widetilde{d}_{Sgi} - \theta_{Ugi} \Delta \ln \widetilde{d}_{Ugi} \right)}_{W_i} = \Delta \ln \widetilde{V}_{Si} / \widetilde{V}_{Ui} \tag{18}$$

where

$$\theta_{fgi} = \left(\frac{\widetilde{d}_{fgi} Q_{gi}}{\widetilde{V}_{fi}} + \frac{\widetilde{d}'_{fgi} Q'_{gi}}{\widetilde{V}'_{fi}} \right) / 2 \ .$$

The θ_{fgi} are factor shares ($\sum_g \theta_{fgi} = 1$) averaged across the two equilibria. The proof is in Appendix E. The B_i term is the *B*etween-industry reallocation effect and corresponds to the output-mix mechanism. The W_i term is the wage effect that leads to *W*ithin-industry substitution towards the cheaper factor. It corresponds to skill-intensity mechanism.

Table 2 reports B_i as a percentage of $\Delta \ln \widetilde{V}_{Si} / \widetilde{V}_{Ui}$. While it varies across countries, on average it accounts for only 2.3% of the absorption of endowments. Thus, our model-based decomposition shows that the skill-intensity mechanism is much more important than the output-mix mechanism.

In Fig. 2 we examine how the results of the model-based decomposition evolved since 1995, which is the first year in which WIOD records data for skilled and unskilled labour. The figure plots the Table 2 numbers on the x-axis and the comparable 1995 numbers on the y axis. Three things stand out. First, the 1995 and 2006 numbers are highly correlated ($\rho = 0.75$). Second, almost all of the data points are below the dashed 45° line, which means that over time the output-mix mechanism has become more important. Third and most important, in both years the share of endowments that are absorbed by the between-industry reallocation mechanism is very small.

We expect that the industry reallocation mechanism will be larger the smaller is σ. In the extreme where skilled and unskilled labour are used in fixed proportions ($\sigma = 0$) we expect that the industry reallocation mechanism dominates entirely. Of course, there is little evidence that $\sigma = 0$ in the data. Acemoglu and Autor (2011, Table 8, column 3) argue with a high degree of confidence that σ is at least as large as 1.55 with a standard error of 0.14. We therefore consider what happens when σ equals 1.3. In the left panel Fig. 3, the x-axis is again our results from Table 2 where we assumed $\sigma = 1.7$. The y-axis is comparable numbers when calibrating the model using $\sigma = 1.3$. We expect the between-industry reallocation mechanism to be more important, which is reflected in the fact that all of the points lie above the 45° line. More importantly, we continue to see that all of the numbers are quite small (below 6.6%) so that the industry reallocation mechanism is small even for some of the smallest σ estimates in the literature.

For completeness we can also ask what happens when σ is larger, say $\sigma = 2$. The results appear in the right panel of Fig. 3. We expect less industry reallocation and this is evident from the fact that almost all the data lie below the 45° line. More importantly, the share of industry reallocation remains largely unchanged for most countries and never exceeds 4.2%. We conclude that in the broad our results are not dependent on the choice of σ.

[17] Costinot et al. (2012) choose $\lambda^{R'}_{gi}$ so that the $\lambda^{R'}_{gi}/\lambda^{R'}_{g'i}$ are the same across countries. This eliminates Ricardian-based comparative advantage. The levels of the $\lambda^{R'}_{gi}$ are then shifted by a country-specific term λ_i to hold incomes constant, which eliminates changes in absolute advantage. We are following Costinot et al. (2012), but with changes in the $\widetilde{V}_{fi}$ taking the place of changes in the $\lambda^{R'}_{gi}$. On a minor note, the change in country i's endowment leads to general equilibrium changes in the wages and prices of *all* countries. Therefore, to hold income shares of all countries constant, we must scale endowments in each country i' by a country-specific term $\lambda_{i'}$. These adjustments are tiny for $i' \neq i$. Again, this is the same procedure as in Costinot et al. (2012).

[18] Factor market clearing is $V_{fi} = \sum_{g=1}^{G} d_{fgi} Q_{gi}$ (Eq. (11)). Multiplying through by λ^V_{fi} yields $\widetilde{V}_{fi} = \sum_g \widetilde{d}_{fgi} Q_{gi}$.

Table 2
Decomposition of endowment differences: industry reallocation share.

Taiwan	4.5%	Austria	3.0%	Germany	2.0%	France	1.3%
Slovakia	4.3%	Ireland	3.0%	Romania	1.7%	Great Britain	1.3%
Slovenia	4.2%	Finland	3.0%	Portugal	1.7%	Italy	1.1%
Belgium	4.1%	Latvia	3.0%	Poland	1.6%	Mexico	0.9%
Malta	4.1%	Cyprus	2.9%	Denmark	1.6%	Spain	0.9%
Netherlands	3.8%	Greece	2.4%	Russia	1.5%	Brazil	0.8%
Bulgaria	3.7%	Czech	2.4%	China	1.5%	Australia	0.7%
Lithuania	3.2%	Hungary	2.2%	Canada	1.5%	Japan	0.7%
Indonesia	3.1%	India	2.1%	Korea	1.3%	United States	0.5%
Estonia	3.1%	Sweden	2.0%	Turkey	1.3%	Mean	2.3%

Each number in the table is a percentage-change comparison between two equilibria, our baseline equilibrium and an equilibrium in which the indicated country has had its endowments moved to the diagonal of the Edgeworth-Bowley box. The table reports the percentage of this endowment change that is accounted for by between-industry change i.e., by industrial reallocation or mechanism (1*a*). Mathematically, the table reports the first term in Eq. (18) as a percentage of the counterfactual change in relative endowments i.e., $100 \cdot B_i / \Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$. 100 minus this number is the percentage of the endowment change accounted for by within-industry change i.e., wage changes that lead to substitution towards the cheaper factor or mechanism (1*b*). All data are model-generated.

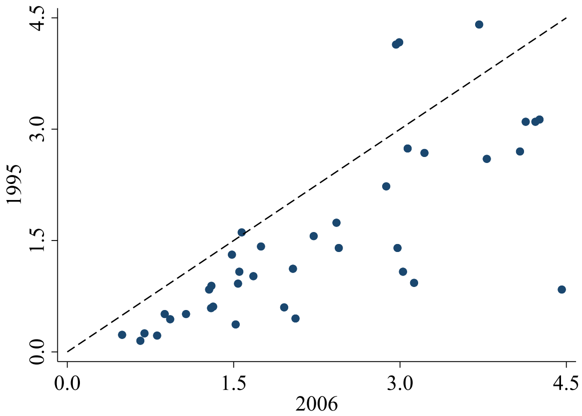

Fig. 2. Decomposition industry reallocation share: 1995 vs. 2006. **Notes:** Each point is a country. The *x*-values are the same as the numbers in Table 2, that is, the 2006 industry reallocations shares $100 \cdot B_i / \Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$. The *y*-values are the comparable numbers for 1995. The dashed line is the 45° line.

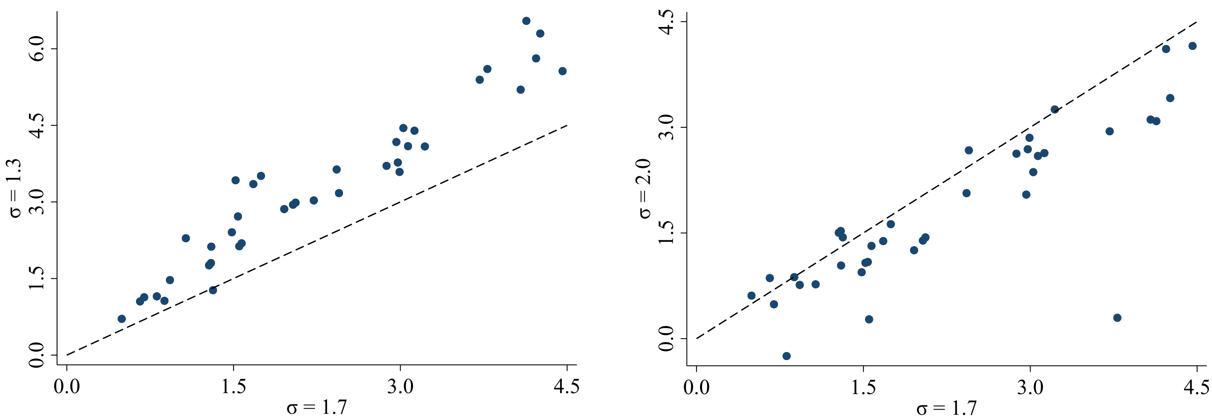

Fig. 3. Decomposition industry reallocation share: different values of σ. **Notes:** Each point is a country. The *x*-values are the same as the numbers in Table 2, that is, the 2006 industry reallocations shares $100 \cdot B_i / \Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$. These assume that the elasticity of substitution between skilled and unskilled labour is $\sigma = 1.7$. In the left panel the *y*-axis is for data from our model calibrated with $\sigma = 1.3$. In the right panel the *y*-axis is for data from our model calibrated with $\sigma = 2.0$. In the right panel Hungary is an outlier and is omitted. The dashed lines are 45° lines.

Our goal in this section was to examine how endowments are absorbed given the presence of features that we see in the real world, meaning a world with trade frictions as well as international technology and preference differences. An alternate approach would be to calibrate the model to a setting where the only source of trade is endowments (i.e., a setting without trade frictions, technology differences, or preference differences) and then do our counterfactual exercise. In theory, this reduces the channels through which adjustment can take place and thus gives greater importance to the industry reallocation mechanism; however, in practice when we implement this approach it does not alter our conclusion that the between-industry output mix mechanism is *much* less important than the within-industry skill-intensity mechanism.

As noted in more detail in the introduction, our decomposition result is consistent with some of the econometric results in the migration literature (Card and Lewis, 2007; Lewis, 2004; Gandal et al., 2004), the trade literature (as surveyed by Goldberg and Pavcnik, 2007), as well as the quantitative results in Parro (2013).[19]

6. A model-based decomposition of skill intensities into wages and technology

We next return to how differences in skill intensities d_{Sgi}/d_{Ugi} are driven by differences in wages w_{Si}/w_{Ui} and skill-biased factor-augmenting technology $\lambda^V_{Si}/\lambda^V_{Ui}$. Our previous thought experiment of reallocating endowments internationally will not help us here because it does not allow the $\lambda^V_{Si}/\lambda^V_{Ui}$ to change.[20] Instead, we switch off the $\lambda^V_{Si}/\lambda^V_{Ui}$ as a source of comparative advantage by setting them to unity. Switching off the $\lambda^V_{Si}/\lambda^V_{Ui}$ leads to both output-mix effects and skill-intensity effects. In Section 6.2 below, we use a similar model-based decomposition as in Table 2 to show that output-mix effects are present but small. This allows us to focus on decomposing the skill intensity effects. The interpretation of the decomposition is then as follows. Eliminating the $\lambda^V_{Si}/\lambda^V_{Ui}$ as a source of comparative advantage has direct and indirect effects on skill intensities. The direct effects are partial equilibrium and hold wages constant. The indirect effects are due to general equilibrium wage changes induced by the technology changes.

Documenting these direct and indirect effects is a new contribution to the literature on international differences in skill intensities e.g., Keesing (1971), Dollar et al. (1988), Wood (1994), Davis and Weinstein (2001) and Lewandowski et al. (2019). In these papers, which largely predate the Eaton-Kortum model, there is no general equilibrium model to help disentangle direct and indirect effects. The direct effects that we measure are similar to what was examined in the pre-Eaton-Kortum HOV literature where the skill-intensity implications of different specifications of technology were examined without modeling general equilibrium wage changes. To cite just a few of many examples, Trefler (1993, 1995) compares the HOV model with and without factor-augmenting international technology differences and Davis and Weinstein (2001) compare the HOV model with and without Hicks neutral international technology differences.[21] We revisit the literature by examining indirect general equilibrium effects.

This section is organized as follows. We first describe our thought experiment of switching off comparative advantage by eliminating variation in $\lambda^V_{Si}/\lambda^V_{Ui}$. This is analogous to how Costinot et al. (2012) switched off comparative advantage by switching off the Ricardian λ^R_{gi}. We then benchmark the impacts of switching off the $\lambda^V_{Si}/\lambda^V_{Ui}$ by comparing their impacts to those from eliminating variation in λ^R_{gi}. In so doing, we show that both are similarly important. Finally, after switching off $\lambda^V_{Si}/\lambda^V_{Ui}$, we decompose the resulting changes in input requirements into direct technology effects and indirect general equilibrium wage effects.

6.1. Switching off technology as a source of comparative advantage

We switch off technology using the approach of Costinot et al. (2012).

1. **Switching Off Factor-Augmenting productivity:** We switch off factor-augmenting productivity as a source of comparative advantage by setting the $\lambda^V_{Si}/\lambda^V_{Ui}=1$ for all countries. In particular, for each country, we set both λ^V_{Si} and λ^V_{Ui} to the mean of the two. As noted by Costinot et al. (2012) this will also affect absolute advantage and we neutralize this by changing each country's aggregate productivity so that the country's new share of world income is the same as its baseline share.[22]

To benchmark the importance of factor-augmenting international productivity, we compare its effect with that of Ricardian international productivity differences. We know that the latter are very important (Costinot et al., 2012), but we have not yet established that the λ^V_{fi} parameters are important. This leads us to our second exercise:

[19] It is less consistent with Hanson and Slaughter (2002) and Burstein et al. (2020). Again, this may be due to the fact that in our cross-country setting relative to their within-US cross-state and cross-commuting-zone, there is likely less scope for migration and weaker forces for factor price equalization.

[20] Since the λ^V_{fi} do not change because they are exogenous parameters, any change in d_{fgi} due to a V_{fi}-induced change in w_{fi} will, by construction, attribute 100% of the change in techniques to wages.

[21] See their specifications P3 and T3.

[22] While shares do not change, expenditure levels do change. A country's expenditure is its share of world expenditures s_i times world expenditures E_w (which equals world income). A country's expenditure s_iE_w thus has two components, one which we do not allow to change (s_i) and one which changes by the same amount for all countries (E_w).

2. **Switching Off Ricardian comparative advantage:** As in Costinot et al. (2012), we switch off Ricardian comparative advantage by setting the $\lambda^R_{gi}/\lambda^R_{g'i}$ equal across countries. In particular, we replace each λ^R_{gi} with a $\lambda^{R'}_{gi}$ that satisfies

$$\frac{\lambda^{R'}_{gi}}{\lambda^{R'}_{g'i}} = \frac{\lambda^{R}_{g,us}}{\lambda^{R}_{g',us}} \qquad \forall g, g', i \ .$$

Again, we change each country's aggregate productivity so that its new share of world income is the same as its baseline share.

6.2. Switching off the $\lambda^V_{Si}/\lambda^V_{Ui}$

Recall that in Eq. (18) we examined how changes in endowments $\Delta \ln \widetilde{V}_{Si}/\widetilde{V}_{Ui}$ lead to changes in output mix (B_i) and skill intensities (W_i). We now do a parallel exercise in which we examine how switching off the factor-augmenting productivities $\lambda^V_{Si}/\lambda^V_{Ui}$ leads to changes in B_i and W_i. As shown in table B3 of the online appendix we again find that B_i is very small confirming the results in Table 2. Across countries the mean value of B_i is 2.8%. For the remainder of this section we examine W_i more closely.

6.3. The importance of $\lambda^V_{Si}/\lambda^V_{Ui}$ relative to λ^R_{gi}

We first compare the impacts of switching off the productivity parameters. It should be easy to see from Eq. (10) that Ricardian productivity has no direct effect on *per dollar* input requirements. In order to place factor-augmenting and Ricardian productivity differences on equal footing, we shift from input requirements *per dollar of output* ($\widetilde{d}_{fgi}$) to input requirements *per unit of output*. The latter is just

$$\bar{d}_{fgi} \equiv \tilde{d}_{fgi} \cdot c_{gi} \ . \tag{19}$$

This is necessary because, for reasons specific to CES, $\widetilde{d}_{fgi}$ depends directly only on λ^V_{fi} and not on λ^R_{gi}. In contrast, $\bar{d}_{fgi}$ depends directly on both.

The results appear in Table 3. Let $\bar{d}_{fgi}$ be a unit input requirement in the baseline equilibrium i.e., with both $\lambda^V_{Si}/\lambda^V_{Ui}$ and λ^R_{gi} switched on. Let $\bar{d}'_{fgi}$ be an input requirement when $\lambda^V_{Si}/\lambda^V_{Ui}$ is switched off in a new equilibrium. Then a measure of the general equilibrium impact of switching off $\lambda^V_{Si}/\lambda^V_{Ui}$ is the log change $\ln(\bar{d}'_{fgi}/\bar{d}_{fgi})$. In Table 3 we report the variance of these log changes calculated across industries and countries. So as not to have results driven by tiny observations (e.g., transportation equipment in Malta) we scale by the square root of Q_{gi}.[23] The first column of the table is the variance of the log change for the case where $\lambda^V_{Si}/\lambda^V_{Ui}$ is switched off. The second column is for the case where λ^R_{gi} is switched off. We can repeat this exercise for any endogenous variable and in the table we do so for nine of the most relevant variables for our decomposition.

We see that $\lambda^V_{Si}/\lambda^V_{Ui}$ is more important than λ^R_{gi} whenever we are dealing with a ratio of skilled to unskilled labour (rows 1, 4 and 7). This should not be surprising given that Ricardian productivity differences do not directly affect relative quantities. For example, the d_{Sgi} and d_{Ugi} are both proportional to λ^R_{gi} so that d_{Sgi}/d_{Ugi} is independent of λ^R_{gi}. In contrast, λ^R_{gi} is as important as $\lambda^V_{Si}/\lambda^V_{Ui}$ when dealing with skilled labour (row 2) and more important when dealing with unskilled labour (row 3). Turning to wages (rows 4–6) and productivity-adjusted wages (rows 7–9), $\lambda^V_{Si}/\lambda^V_{Ui}$ is more important than λ^R_{gi} except when dealing separately with productivity-adjusted skilled and unskilled labour (rows 8-9). In short, $\lambda^V_{Si}/\lambda^V_{Ui}$ is roughly as important as the heavily studied λ^R_{gi} in these dimensions. This is true both in 2006 and 1995.

6.4. Decomposition into direct and general equilibrium effects

We now decompose changes in $\bar{d}_{fgi}$ into direct and general equilibrium effects to examine the distinct impacts of wages and technology on input requirements. To do this, we start by decomposing the total log change in $\bar{d}'_{fgi}/\bar{d}_{fgi}$ as follows:

$$\ln\left(\frac{\bar{d}'_{fgi}}{\bar{d}_{fgi}}\right) = \ln\left(\frac{\bar{d}^D_{fgi}}{\bar{d}_{fgi}}\right) + \ln\left(\frac{\bar{d}^P_{fgi}}{\bar{d}^D_{fgi}}\right) + \ln\left(\frac{\bar{d}'_{fgi}}{\bar{d}^P_{fgi}}\right) \tag{20}$$

where we now describe $\bar{d}^D_{fgi}$ and $\bar{d}^P_{fgi}$. Recall that $\bar{d}_{fgi}$ depends on wages and price indexes (P_{gi}) and that wages and price indexes vary endogenously as we switch off the productivity parameters. $\bar{d}^D_{fgi}$ is $\bar{d}_{fgi}$ evaluated at the new productivity parameters, but the initial wages and prices. Likewise, $\bar{d}^P_{fgi}$ is $\bar{d}_{fgi}$ evaluated at the new productivity parameters and price indexes, but at initial wages.

[23] Scaling is a minor point – we obtain almost identical results if instead of weighting we omit tiny observations.

Table 3
Total effects.

	2006		1995	
	Switch off $\lambda^V_{Si}/\lambda^V_{Ui}$	Switch off λ^R_{gi}	Switch off $\lambda^V_{Si}/\lambda^V_{Ui}$	Switch off λ^R_{gi}
Inputs per unit of output				
1. $\bar{d}_{Sgi}/\bar{d}_{Ugi}$	0.68	0.02	1.00	0.00
2. $\bar{d}_{Sgi}$	0.33	0.27	0.68	0.17
3. $\bar{d}_{Ugi}$	0.09	0.23	0.05	0.16
Wages				
4. w_{Si}/w_{Ui}	0.10	0.006	0.15	0.00
5. w_{Si}	0.05	0.002	0.10	0.00
6. w_{Ui}	0.01	0.001	0.01	0.00
Productivity-adjusted wages				
7. $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$	0.23	0.01	0.34	0.00
8. $\widetilde{w}_{Si}$	0.10	0.37	0.22	0.22
9. $\widetilde{w}_{Ui}$	0.03	0.31	0.02	0.21

Each entry is the weighted variance of the log change in the indicated outcome as we move from the baseline equilibrium to the equilibrium in which either $\lambda^V_{Si}/\lambda^V_{Ui}$ is switched off (first column) or λ^R_{gi} is switched off (second column). As an example, consider the unit input requirements for skilled labour in row 2. Let $\bar{d}_{Sgi}$ be its baseline value and $\bar{d}'_{Sgi}$ be its value when $\lambda^V_{Si}/\lambda^V_{Ui}$ is switched off. Then 0.33 is the variance of $\ln(\bar{d}_{Sgi}/\bar{d}'_{Sgi})$ calculated across industries g and countries i. Likewise, 0.27 is the corresponding variance when λ^R_{gi} is switched off. In calculating weighted variances, the weights are the square root of Q_{gi} (rows 1-3) or $\sum_g Q_{gi}$ (rows 4-9).

Appendix F provides mathematical expressions for $\bar{d}^D_{fgi}$ and $\bar{d}^P_{fgi}$. Therefore, the first term on the right side of the above equation is the log change in unit requirements holding wages and price indexes at their initial levels. The second term is the additional log change due to changes in the price index, holding wages at their initial levels. It is one way of isolating the role of input-output linkages emphasized by Caliendo and Parro (2015). The third term is the additional log change due to changes in wages.

Taking the variance of both sides of the above equation yields

$$\mathcal{T} = \mathcal{D} + \mathcal{P} + \mathcal{W} + \mathcal{C}$$

where $\mathcal{T}$, $\mathcal{D}$, $\mathcal{P}$ and $\mathcal{W}$ are the variances of the four terms in Eq. (20) and $\mathcal{C}$ collects the covariance terms. It is convenient to divide through by the total variance in order to express elements of the decomposition as shares:

$$1 = \frac{D}{\mathcal{T}} + \frac{P}{\mathcal{T}} + \frac{W}{\mathcal{T}} + \frac{C}{\mathcal{T}}. \tag{21}$$

Table 4 reports the elements of this equation multiplied by 100. The $\mathcal{D}/\mathcal{T}$, $\mathcal{P}/\mathcal{T}$, and $\mathcal{W}/\mathcal{T}$ columns must be non-negative and the four columns must sum to 100%. Consider the first row of Table 4, which deals with the variance of log changes in $\ln(\bar{d}_{Sgi}/\bar{d}_{Ugi})$. Again, the variance is pooled across industries and countries and weighted by Q_{gi}. The first column shows that 280% of this variance is due to the direct partial equilibrium effect holding wages and price indexes constant. The second

Table 4
Direct and general equilibrium effects.

	Panel A: switch off λ^V_{fi}				Panel B: switch off λ^R_{gi}			
	$\mathcal{D}/\mathcal{T}$	$\mathcal{P}/\mathcal{T}$	$\mathcal{W}/\mathcal{T}$	$\mathcal{C}/\mathcal{T}$	$\mathcal{D}/\mathcal{T}$	$\mathcal{P}/\mathcal{T}$	$\mathcal{W}/\mathcal{T}$	$\mathcal{C}/\mathcal{T}$
				Inputs per unit of output				
1. $\bar{d}_{Sgi}/\bar{d}_{Ugi}$	280	0	45	−225	0	0	100	0
2. $\bar{d}_{Sgi}$	247	1	38	−186	31	13	45	12
3. $\bar{d}_{Ugi}$	327	3	54	−284	37	15	31	17
				Wages				
4. w_{Si}/w_{Ui}	0	0	100	0	0	0	100	0
5. w_{Si}	0	0	100	0	0	0	100	0
6. w_{Ui}	0	0	100	0	0	0	100	0
				Productivity-adjusted wages				
7. $\widetilde{w}_{Si}/\widetilde{w}_{Ui}$	280	0	45	−225	0	0	100	0
8. $\widetilde{w}_{Si}$	220	0	25	−144	0	0	100	0
9. $\widetilde{w}_{Ui}$	404	0	108	−412	0	0	100	0

Each row is a different endogenous equilibrium outcome. We switch off either λ^V_{fi} or λ^R_{gi} and calculate the total variance of the log change in the row's outcome. The total variance appeared above in Table 3. In this table we decompose the total variance into a direct effect $\mathcal{D}/\mathcal{T}$, a price-index effect $\mathcal{P}/\mathcal{T}$, a wage effect $\mathcal{W}/\mathcal{T}$ and a covariance term $\mathcal{C}/\mathcal{T}$. See Eq. (21). These effects are multiplied by 100 to express them as percentages of the total variance. Within each panel, the first three columns must be non-negative and the sum across the four columns must be 100. One can prove theoretically that 0 entries must be zero.

column shows that 0% of the variance is due to general equilibrium changes in price indexes. This is because P_{gi} does not show up in the expression for *relative* input requirements. The third column shows that 45% of the variance is due to general equilibrium changes in wages. The fourth column shows that −225% of the variance is due to general equilibrium effects underlying the covariance term. The shares of 280% and −225% are at first glance surprising, but have a simple interpretation. The direct effect induces a change in unit input requirements, say an increase in unit requirements of skilled labour. This raises skilled wages which in turn reduces skill intensities. This latter negative correlation between skilled wages and skilled requirements shows up in the negative covariance term −225%. Further, since the covariance term is negative, the remaining terms must sum to more than 100% and this shows up in the 280% direct effect.

For Ricardian productivity (Panel B), the results are similarly intuitive. Ricardian productivity differences have no direct effect on relative techniques nor any effect through prices (row 1) as top and bottom 'cancel out' for relative techniques. However, Ricardian differences do affect unit inputs (rows 2 and 3). The last three columns then show the endogenous effects of price indexes and wages. For unit input requirements, the direct effects and general-equilibrium wages effects are larger, with smaller general-equilibrium price-index effects and covariance effects.

The first three rows of Table 4 contain the main point of the table. They show that switching off the productivity parameters, especially the $\lambda_{Si}^V/\lambda_{Ui}^V$, induces large general equilibrium feedback effects on unit input requirements. As a result, the older literature on the role of international technology differences for international differences in unit input requirements missed very important general equilibrium wage and price effects.

The remaining rows of Table 4 report results for wages and productivity-adjusted wages. The results are intuitive. In rows (4)-(6) of Panel A, it is trivial that 100% of the variance in wages is accounted for by general equilibrium wage adjustment. In rows (7)-(9), changes in factor-augmenting productivity, have a large direct effect on productivity-adjusted wages, but the endogenous response of observed wages induces a strong adjustment in the opposite direction.

There are three takeaways from this section. First, the output-mix effects of eliminating differences in $\lambda_{Si}^V/\lambda_{Ui}^V$ as a force for comparative advantage are small. Second, while the pre-Eaton-Kortum factor endowments literature largely explored the direct relationship between productivity and unit input requirements, it did not have the modelling tools to fully examine the general equilibrium aspects of this relationship. We show that these aspects are of first-order and offsetting importance (Table 4). Third, factor-augmenting productivity $\lambda_{Si}^V/\lambda_{Ui}^V$ is comparable in importance to Ricardian productivity λ_{gi}^R for thinking about unit input requirements, wages, and productivity-adjusted wages. See Table 3. Summarizing, Tables 3 and 4 show that factor-augmenting technology is important and explains a substantial portion of the international variation in skill intensities, both directly as well as indirectly through general equilibrium impacts on wages.

7. The Heckscher-Ohlin trade prediction

The finding that industrial reallocation (mechanism 1a) is small means that trade movements are not that important for thinking about how an economy absorbs its endowments. Does this mean that the Heckscher-Ohlin forces documented by Romalis (2004) and Morrow (2010) do not hold in our setting? The answer is a resounding "no." In the 2 × 2 Heckscher-Ohlin model skill-abundant countries export skill-intensive goods. While this is not a theoretically derivable implication of our model, we can ask whether it holds quantitatively as we switch off endowments-based comparative advantage. To this end, we take the endowments of all countries and move them to the diagonal of the Edgeworth-Bowley box, meaning, we choose new endowments

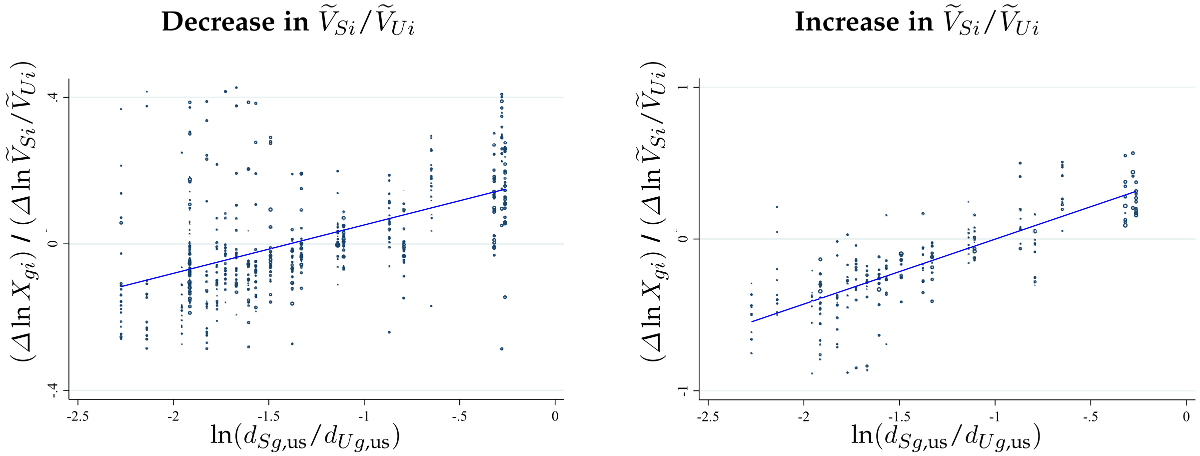

Fig. 4. A counterfactual assessment of the Heckscher-Ohlin trade prediction. **Notes:** Each marker is an industry in a country. Marker size is proportional to export shares $X_{gi}/\sum_{g'}X_{g'i}$ so that each country's largest trade flows appear more prominently. The line of best fit is also displayed and is based on a weighted least squares regression with weights equal to the square root of export shares. The R^2 are 0.25 in the left panel and 0.71 in the right panel. The slopes are statistically significant at the 1% level using standard errors that are two-way clustered by industry and country.

$\widetilde{V}'_{Si}/\widetilde{V}'_{Ui}$ satisfying $\widetilde{V}'_{Si}/\widetilde{V}'_{Ui} = \widetilde{V}_{Sw}/\widetilde{V}_{Uw}$ while holding each country's share of world income constant. See the discussion surrounding Eq. (17).

Let X_{gi} be country i's gross exports of g and define $\Delta \ln X_{gi} \equiv \ln X_{gi} - \ln X'_{gi}$. Fig. 4 plots model-generated $\Delta \ln X_{gi}/\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$ against US skill intensity $d_{Sg,\text{us}}/d_{Ug,\text{us}}$. Each point is an industry-country pair. We expect a positive relationship: As a country becomes more skill abundant, it increases its exports of skill-intensive goods and reduces its exports of unskilled-intensive goods. Note that $\Delta \ln X_{gi}$ and $\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})$ have the same sign for skill-intensive industries and opposite signs for unskilled-intensive industries so data should lie either in the top right or bottom left, generating an upward sloping relationship. As shown in Fig. 4, the relationship is strong and upward-sloping as expected. The left panel plots data for countries with $\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})<0$. The right panel plots data for countries with $\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui})>0$. We conclude that there is a 2 × 2 Heckscher-Ohlin trade result in operation in the model. Relative endowments have an effect on the structure of trade and production.

There are some large outliers which we do not include in Fig. 4. First, we trim the top and bottom 5% of industry-country observations. Most of these involve industries that are minor for the country. For example, less than 1% of Latvian energy comes from coal or nuclear power and the model predicts that the value of this sector shrinks basically to zero (from a small 4.1 to a tiny 0.07), resulting in $\Delta \ln X_{gi}/\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui}) = 14.2$ or 14 times larger than any other observation in Fig. 4. Second, we omit the four countries for which $\Delta \ln(\widetilde{V}_{Si}/\widetilde{V}_{Ui}) \approx 0$ since these have many outliers yet convey little information about Heckscher-Ohlin mechanisms.[24]

This exercise has the flavour of the Heckscher-Ohlin theorem. Note, however, that in that theorem wages and prices are being held constant. That is not the case here where they adjust to new equilibrium values as endowments change. Also, underlying the Heckscher-Ohlin theorem is the Rybczynski theorem which deals with output adjustments. It is therefore of interest that when we replace ΔX_{gi} with ΔQ_{gi} we get similar results.

An alternative is to run a regression motivated by Romalis (2004) using actual data. Specifically, modify Eq. (13) by introducing a Romalis-inspired interaction between factor intensities ($d_{Sg,\text{us}}/d_{Ug,\text{us}}$) and factor abundance ($V_{Si}/V_{Ui}$):

$$\ln \pi_{gi,j} = \beta \ln \frac{d_{Sg,\text{us}}}{d_{Ug,\text{us}}} \cdot \ln \frac{V_{Si}}{V_{Ui}} + \delta_{gj} + \delta_{ij} + \varepsilon_{gi,j}$$

where we expect $\beta > 0$ because country i is a low-cost producer of good g if i is skill-abundant and g is skill-intensive. In this regression, we control for destination-good gj and origin-destination ij fixed effects. In our data we estimate $\beta = 0.67$ with standard error 0.11 where clustering is three way by gi, gj and ij. One- and two-way clustered standard errors are very similar. We again conclude that there is a Heckscher-Ohlin trade result in operation. We also conclude that our finding of a Heckscher-Ohlin effect does not conflict with our statement that it is not a dominant mechanism by which endowments are absorbed.

8. A note on directed technical change

In this paper we treat the $\lambda^V_{Si}/\lambda^V_{Ui}$ as exogenous productivity parameters. In this section, we briefly and informally relax this assumption by relating our approach to the large literature on directed technical change (Acemoglu, 1998, 2009). This literature, summarized in Acemoglu (2009, chapter 15), explains how $\lambda^V_{Si}/\lambda^V_{Ui}$ may respond to endowments V_{Si}/V_{Ui}. There are two offsetting effects of endowments on technology. On the one hand, innovation is directed towards the expensive factor (the price effect). On the other hand, innovation is directed towards the more abundant factor (the market-size effect). If $\sigma > 1$, the market-size effect dominates so that technical change is directed towards a country's abundant factor. See Acemoglu (1998, 2009) and, in an international context, Acemoglu and Zilibotti (2001), Gancia and Bonfiglioli (2008), Gancia and Zilibotti (2009) and Blum (2010).[25] While it is beyond the scope of this paper to model directed technical change, we can take a reduced-form approach by appealing to the model in Acemoglu (2009, chapter 15). Consider a closed economy which behaves as if the aggregate production function $Y_i = \left[\alpha_U (\lambda^V_{Ui} V_{Ui})^{\frac{\sigma-1}{\sigma}} + \alpha_S (\lambda^V_{Si} V_{Si})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$ holds.[26] Firms decide whether to innovate towards increasing the productivity of S or U depending on aggregate relative endowments of the two factors as well as, critically, on the elasticity of substitution σ.

[24] To understand why, note that country i's $\Delta \ln X_{gi}$ has two components. There is a 'direct' component due to the change in i's endowments, which is the focus of the Heckscher-Ohlin theorem. There is also an 'indirect' component due to the change in the endowments of all other countries $j \neq i$, which is not the focus of the theorem. For countries with $\Delta \ln(\widetilde{V}_{\text{Si}}/\widetilde{V}_{\text{Ui}}) \approx 0$, the direct component is approximately zero, but the indirect component can be large, especially for trading partners of China. (As China moves to the Edgeworth-Bowley diagonal, China becomes hugely more skill abundant, which sends ripples throughout the global economy.) Therefore, for $\Delta \ln(\widetilde{V}_{\text{Si}}/\widetilde{V}_{\text{Ui}}) \approx 0$ countries, $\Delta \ln X_{gi}/\Delta \ln(\widetilde{V}_{\text{Si}}/\widetilde{V}_{\text{Ui}})$ involves a non-zero numerator and an approximately zero denominator, causing it to blow up for reasons that tell us very little about the direct Heckscher-Ohlin mechanisms. This issue is just an artifact of trying to display the 2×2 Heckscher-Ohlin mechanism compactly in a multi-country, multi-industry setting. The four omitted countries are those with $|\Delta \ln(\widetilde{V}_{\text{Si}}/\widetilde{V}_{\text{Ui}})| \leq 0.05$. This is not an issue in Table 2 as countries' endowments are only moved one-by-one for each entry.

[25] The directed technical change mechanism is different from the Burstein and Vogel (2017) mechanism: In the former it is a choice while in the latter it is not a choice but a technological feature of size. Given the complexity of the underlying trade model, the Burstein and Vogel (2017) is an impressive modelling simplification.

[26] Acemoglu has two sectors and sector f produces output using machines and factor f. Firms in sector f choose how much to innovate and innovation raises the productivity of factor f i.e., raises λ^V_{fi}. The output of the two sectors are aggregated using a CES production function. This aggregate production function implies a derived elasticity of substitution between capital and labour σ which is the inverse of the elasticity of relative wages with respect to endowments i.e., Acemoglu's derived elasticity σ is the same as our elasticity σ. For more details see the discussion following Acemoglu's equation 15.19.

Acemoglu (2009, eq. 15.27) derives the following equation, which contains most of the economics of directed technical change:

$$\ln \frac{\lambda_{Si}^{V}}{\lambda_{Ui}^{V}} = \beta_0 + (\sigma - 1)\ln\left(\frac{V_{Si}}{V_{Ui}}\right) \tag{22}$$

where β_0 is an exogenous parameter of Acemoglu's model and σ is the (derived) elasticity of substitution.

To investigate, we estimate Eq. (22) using our 39 countries/observations and estimates of $\lambda_{Si}^{V}/\lambda_{Ui}^{V}$. The R^2 is 0.17 and the coefficient on log relative endowments is 0.50 with a standard error of 0.18. The estimated coefficient implies $\sigma - 1 = 0.50$ or $\sigma = 1.50$, which is close to the Acemoglu and Autor (2011) midpoint estimate of 1.70 that we use. We conclude from this that the actual data display a correlation between endowments and technology which is in the same direction as that emphasized in the directed technical change literature.

9. Theoretical predictions for trade in factor services

In this section, we examine whether using actual data that incorporates both factor-augmenting and Ricardian productivity differences resolves “missing trade.” We find that it does not and, using our model, offer evidence that trade costs are the primary determinant of missing trade and not differences in preferences. We start by defining familiar expressions for the factor content of trade before moving to our empirical analysis.

9.1. The world input-output accounts

Let $\boldsymbol{B}$ be the world input-output matrix. The fundamental input-output equation states that gross output ($\boldsymbol{Q}_i$) is used for intermediate inputs ($\boldsymbol{BQ}_i$), final consumption ($\boldsymbol{C}_i$) and trade ($\boldsymbol{T}_i$). That is, $\boldsymbol{Q}_i = \boldsymbol{BQ}_i + \boldsymbol{C}_i + \boldsymbol{T}_i$ or

$$\boldsymbol{T}_i = (\boldsymbol{I} - \boldsymbol{B})\boldsymbol{Q}_i - \boldsymbol{C}_i \tag{23}$$

where $\boldsymbol{I}$ is an identity matrix. More specifically, $\boldsymbol{B}$ is a $GN \times GN$ matrix whose (gi, hj) element $b_{gi,hj}$ is the value of intermediate inputs (g, i) needed per dollar of (h, j) output. $\boldsymbol{Q}_i$ is a GN column vector whose gi element is Q_{gi} and whose gj element for $j \neq i$ is zero. $\boldsymbol{C}_i$ is a GN column vector whose gj element $C_{gj,i}$ is the value of country i's consumption of good g produced in country j. $\boldsymbol{T}_i$ is a GN column vector whose gi element X_{gi} is the value of country i's exports of g and whose gj element for $j \neq i$ is $-M_{gj,i}$, the negative of country i's imports of g from j.[27] Eq. (23) is the goods market clearing condition and always holds in both the data and the quantitative model. Appendix D.3 sets up these vectors and matrices in more detail and equates their elements back to primitives of the model so that it is clear how they are simulated in our quantitative model.

9.2. The vanek factor content of trade prediction

Following Trefler and Zhu (2010), we define the Vanek-consistent factor content of trade as the factors employed *worldwide* to produce country i's trade flows $\boldsymbol{T}_i$. Letting $\boldsymbol{D}_f$ be a $1 \times GN$ matrix with typical element d_{fgi} and defining $\boldsymbol{A}_f \equiv \boldsymbol{D}_f(\boldsymbol{I} - \boldsymbol{B})^{-1}$, the Vanek-consistent factor content of trade is

$$F_{fi} \equiv \boldsymbol{A}_f \boldsymbol{T}_i. \tag{24}$$

It is ‘Vanek-consistent’ because, as the next theorem shows, under certain conditions F_{fi} equals its Vanek prediction $V_{fi} - s_i \sum_j V_{fj}$ where s_i is country i's share of world consumption ($\sum_i s_i = 1$).

Theorem 1. Trefler and Zhu (2010):

$$F_{fi} = \left(V_{fi} - s_i \sum_{j=1}^{N} V_{fj}\right) + \boldsymbol{A}_f(\boldsymbol{C}_i - s_i \boldsymbol{C}_w). \tag{25}$$

The proof appears in Appendix G. $\boldsymbol{C}_i = s_i \boldsymbol{C}_w$ is a sufficient condition for the Vanek equation to hold. To better understand the condition, note that $\boldsymbol{C}_j = s_j \boldsymbol{C}_w$ in non-matrix notation is $C_{gi,j} = s_j C_{gi,w}$ for all g and i, meaning that country j's consumption is proportional to world consumption and the proportion s_j is the same for all goods g from all locations i. If there are no intermediate inputs then all inputs are for consumption ($M_{gi,j} = C_{gi,j}$) and all production is consumed somewhere in the world ($Q_{gi} = C_{gi,w}$) so that $C_{gi,j} = s_j C_{gi,w}$ is just the gravity equation (without distance) $M_{gi,j} = s_j Q_{gi}$.

[27] The subscripts are dense, but keeping track of them is unimportant for what follows.

Theorem 1 answers the confusing question about whether the Vanek equation is an accounting identity or a testable prediction. In the following corollary, we show that when preferences are identical internationally and when there are no trade costs in our model, then $\boldsymbol{C}_i = s_i\boldsymbol{C}_W$ i.e., the Vanek prediction holds with identity.

Corollary 1. *Suppose that preferences are identical internationally (γ^U_{gi} is independent of i for all g) and that there are no trade costs ($\tau_{gi,j} = 1$ for all g, i and j). Then $\boldsymbol{C}_i = s_i\boldsymbol{C}_W$ and*

$$F_{fi} = V_{fi} - s_i \sum_{j=1}^{N} V_{fj} \ .$$

The proof appears in Appendix G.

While the Vanek equation is an identity in the data when preferences are internationally identical and there are no trade costs, it is nevertheless of empirical interest for three reasons. First, in the real world that generated the WIOD data, there are large trade costs so the Vanek equation does not hold as an accounting identity. The Vanek equation can thus be tested using WIOD data. Note that this is equivalent to testing $\boldsymbol{C}_i = s_i\boldsymbol{C}_W$. Also note that if $\boldsymbol{C}_i \neq s_i\boldsymbol{C}_W$, then the error term is $\boldsymbol{A}_f(\boldsymbol{C}_i - s_i\boldsymbol{C}_W)$, which does depend on technology via $\mathbf{A}_f$. Second, corollary 1 leaves open the question of whether the failure of the Vanek equation is due to trade costs or international preference differences. We use our quantitative model to show that the failure is almost entirely the result of trade costs. Third, it is an open question whether the Vanek equation would come close to holding if trade costs were partially but not fully eliminated.[28]

9.3. The empirics of trade in factor services

We now turn to empirics. We start by replicating past results for trade in factor services in this section. Trade in factor services is given by Corollary 1. Consider the left panels of Fig. 5 which plot the factor content of trade F_{fi} (vertical axis) against its Vanek predictor $V_{fi} - s_iV_{fw}$ (horizontal axis). Both F_{fi} and $V_{fi} - s_iV_{fw}$ are scaled by V_{fi}. The top left panel is for unskilled labour, each point is a country, and we are plotting actual data (not model-generated data). The panel displays a strong positive relationship between endowments and factor contents and, correspondingly, the OLS line of best fit has a remarkably high R^2 of 0.90. In contrast, the best-fit line has a slope that is much below unity (slope = 0.17, s.e. = 0.01), which means that there is much less trade in factor services than predicted by the theory. Missing trade is in evidence. Similar conclusions emerge for skilled labour, which is plotted in the middle-left panel.

Recall that the spirit of Heckscher-Ohlin is about the impact of *relative* factor abundance i.e. of abundance of skilled labour *relative* to unskilled labour. This has never been examined in a Vanek context. In the bottom-left panel we plot $(F_{Si}/V_{Si}) - (F_{Ui}/V_{Ui})$ against $(V_{Si} - s_iV_{Sw})/V_{Si} - (V_{Ui} - s_iV_{Uw})/V_{Ui}$. There is clearly a strong positive relationship between relative endowments and the relative factor content of trade. The R^2 of 0.90 is high, but again missing trade is evidenced by the slope of 0.18.

Before turning to missing trade, there are a number of points that need to be addressed. We display the scaled plots because the unscaled plots are visually dominated by the two largest countries, China and the United States. That said, the unscaled results lead to exactly the same conclusions: The R^2s for unskilled labour, skilled labour and skilled less unskilled labour are 0.93, 0.98, and 0.92, respectively, and the slopes are 0.17 (0.01), 0.13 (0.003), and 0.17 (0.01).

As before, we measure endowments in efficiency units before summing them to the world level: $\widetilde{V}_{fw} = \sum_i \widetilde{V}_{fi}$. Recall that the only place the d_{fgi} and V_{fi} appear in the model is in the factor-market clearing equation $\sum_g d_{fgi}Q_{gi} = V_{fi}$. Multiplying through by λ^V_{fi} yields $\sum_g \widetilde{d}_{fgi}Q_{gi} = \widetilde{V}_{fi}$. This means that $F_{fi} = V_{fi} - s_iV_{fw}$ iff

$$\widetilde{F}_{fi} = \widetilde{V}_{fi} - s_i\widetilde{V}_{fw} \tag{26}$$

where $\widetilde{F}_{fi}$ is computed in the same way as F_{fi} but using $\widetilde{d}_{fgi}$ in place of d_{fgi}. See Trefler (1993). This prediction sums U.S. and Indian labour only after measuring them in comparable, productivity-adjusted units. The right panels of Fig. 5 repeat the left panels, but now plotting $\widetilde{F}_{fi}/\widetilde{V}_{fi}$ against $(\widetilde{V}_{fi} - s_i\widetilde{V}_{fw})/\widetilde{V}_{fi}$. This does not change our conclusions.

9.4. The role of trade costs and preferences

The preceding sections explored the determinants of the supply side of the Vanek equation. However, we know from Fig. 5 that the Vanek equation displays an abundance of missing trade even if we fit the supply side perfectly by using actual data.

We now turn to the quantitative model to ask and answer two questions. First, to what extent is the failure of the Vanek prediction due to trade costs as opposed to international preference differences. Corollary 1 established the new result that, as an

[28] The ideas in this subsection were anticipated by Deardorff (1982), Helpman and Krugman (1985), Trefler (1996), Feenstra (2004), Trefler and Zhu (2010), and Burstein and Vogel (2011). See especially Feenstra (2004)'s ([p. 56]Feenstra, 2004) comment that imposing gravity without distance on the data (which is close to imposing $\mathbf{C}_i = s_i\mathbf{C}_w$) comes close to a hypothesis about an identity. Staiger et al. (1987) anticipated our quantitative strategy using the Michigan Model; however, they arrived at the surprising and opposite conclusion that tariff reductions worsen the fit of the Vanek equation.

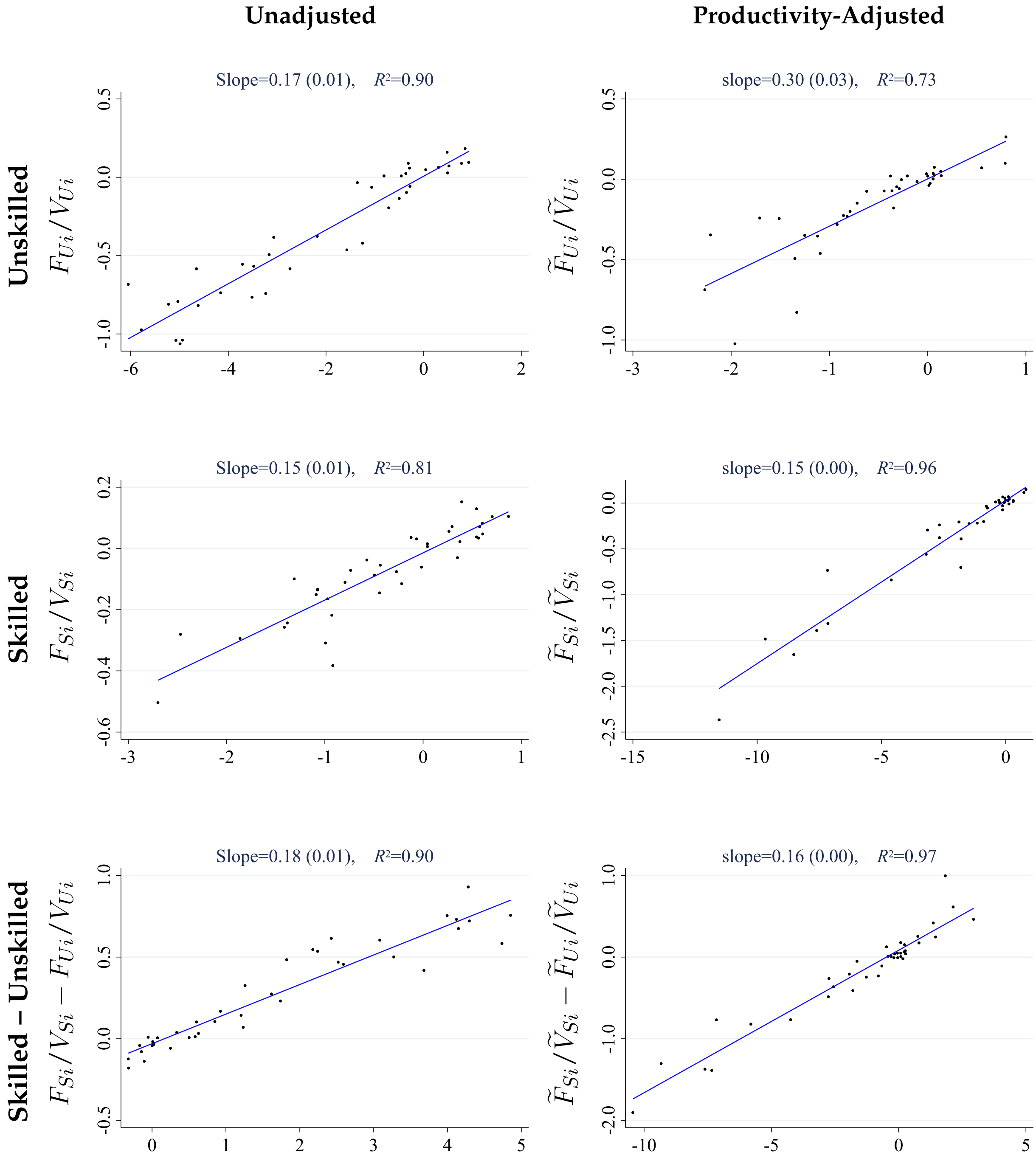

Fig. 5. The Vanek Equation. **Notes:** The top left panel plots F_{Ui}/V_{Ui} on the vertical axis against $(V_{Ui} - s_iV_{Uw})/V_{Ui}$ on the horizontal axis. Each point is a country. Actual data (rather than model-generated data) are plotted. The top right panel plots the same, but in productivity-adjusted units: $\widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ against $(\widetilde{V}_{Ui} - s_i\widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. The middle two panels repeat this for skilled labour. The bottom left panel plots the difference between skilled and unskilled labour, $[(F_{Si}/V_{Si}) - (F_{Ui}/V_{Ui})]$ against $[(V_{Si} - s_iV_{Sw})/V_{Si}] - [(V_{Ui} - s_iV_{Uw})/V_{Ui}]$. The bottom right panel plots the same, but in productivity-adjusted units. The OLS line of best fit is displayed along with its slope (standard error) and R^2.

identity, the failure of the Vanek prediction must be due some mix of these two factors. To answer this we switch off trade costs ($\tau_{gi,j} = 1$ for all g, i and j) and re-simulate the model to obtain model-generated data for $\widetilde{F}_{Si}/\widetilde{V}_{Si} - \widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ and $(\widetilde{V}_{Si} - s_i\widetilde{V}_{Sw})/\widetilde{V}_{Si} - \widetilde{F}_{Ui}(\widetilde{V}_{Ui} - s_i\widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. The left panel of Fig. 6 plots this. The fit is almost perfect, which means that *the failure*

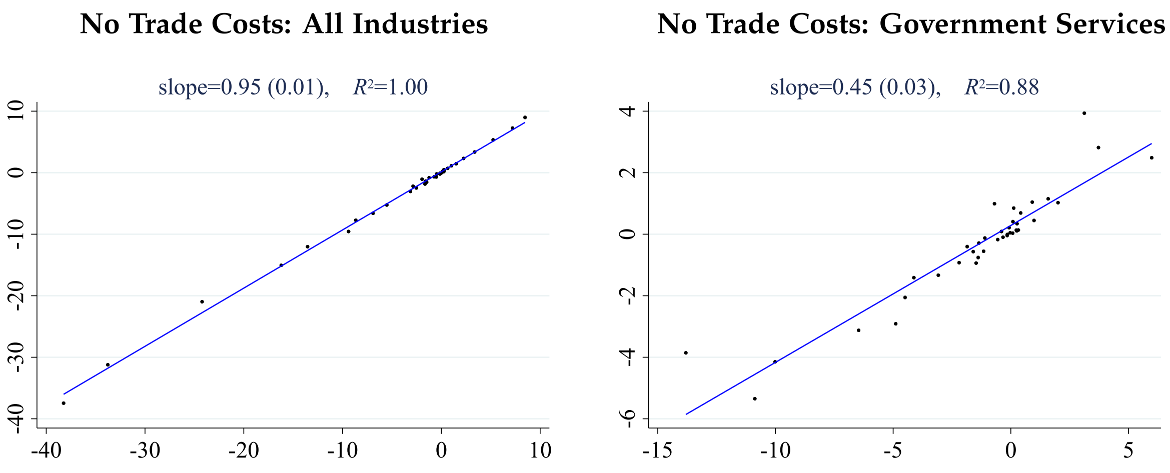

Fig. 6. Vanek Equation: role of trade costs and preferences. **Notes:** The panels plots $\widetilde{F}_{Si}/\widetilde{V}_{Si}-\widetilde{F}_{Ui}/\widetilde{V}_{Ui}$ on the vertical axis against $(\widetilde{V}_{Si}-s_i\widetilde{V}_{Sw})/\widetilde{V}_{Si}-(\widetilde{V}_{Ui}-s_i\widetilde{V}_{Uw})/\widetilde{V}_{Ui}$. In the left panel, the points are model-generated data from an equilibrium in which trade costs have been eliminated in every sector ($\tau_{gi,j}=1$). In the right panel, the points are model-generated data from an equilibrium in which trade costs have been eliminated only in the Government Services sector. For skilled and unskilled labour separately in the right panel the slopes are 0.73 and 0.68, respectively, and the R^2s are 0.96 and 0.92, respectively. The results without productivity adjustments are very similar. The OLS line of best fit is displayed as is its slope (standard error) and R^2. For the purposes of display Malta is not shown in either panel: It lies on the line of best fit but is far to the bottom left.

of the Vanek prediction is almost entirely driven by the presence of trade costs and to basically no degree by the presence of international preference differences.[29]

Second, Trefler and Zhu (2010) observe that the failure of the Vanek equation is largely driven by just a few sectors, namely, Agriculture, Government Services, and Construction. We can use our quantitative model to investigate this claim in general equilibrium. In particular, we ask what would happen in general equilibrium if all trade costs in Government Services were eliminated. We chose Government Services because System of National Accounts manuals instruct national statistical agencies to define Government Services as non-tradable government services.[30] We thus eliminate all trade costs for Government Services ($\tau_{\text{Govt }i,j}=1$), re-simulate the model and plot as in the left panel of Fig. 6. The results appear in the right panel. The slope rises from 0.18 to 0.44, that is, a large chunk of missing trade is explained solely by a single non-traded sector.

10. Conclusion

The answers to many key questions in international trade depend on the size of the components of two decompositions:

1. Differences in how countries absorb their endowments of skilled and unskilled labour can be decomposed into (a) differences in the skewness of output mix towards skill-intensive industries and (b) differences in the skill intensity of each industry.
2. Within each industry, cross-country differences in skill intensities can be decomposed into contributions from cross-country differences in (a) relative wages and (b) skill-biased, factor-augmenting technology.

We provided evidence from a quantitative trade model that the output-mix component is small, that the relative wage and factor-augmenting technology components are large, and that some of the relative wage component is induced by the indirect general equilibrium impacts on wages of factor-augmenting international technology differences. Along the way we developed a new method of estimating factor-augmenting technology differences. In conclusion, for the question of how countries absorb their endowments, factor-augmenting international technology differences and wages play a critical role while output mix plays a more modest role.

[29] We obtain the exact same conclusion from plotting $\widetilde{F}_{fi}/\widetilde{V}_{fi}$ against $(\widetilde{V}_{fi}-s_i\widetilde{V}_{\text{fw}})/\widetilde{V}_{fi}$ for $f=S,U$. We also obtain the exact same result without the productivity adjustment.

[30] More exactly, System of National Accounts manuals instruct national statistical agencies to exclude from this sector all government services that are sold via market transactions. By way of example, Canadian postal services are sold to the public but police services are not so that Government Services excludes the post office but not the police. Since by this definition Government Services are not sold on markets, they are nontraded — we do not see California state troopers patrolling the streets of São Paolo.

Appendix A. Expression for expenditure

Proof of Eq. (8). Part 1: Country j's expenditure power is $E_j \equiv w_{Sj}V_{Sj} + w_{Uj}V_{Uj} + D_j$ i.e., income from primary factors plus exogenous deficit spending. From the cost function (Eq. (5)), primary factor income generated in (h, j) is a fraction γ^V_{hj} of costs and hence of sales Q_{hj}.[31] Hence primary income in j is $\sum_{h=1}^{G}\gamma^V_{hj}Q_{hj}$ and $E_j = \sum_h \gamma^V_{hj}Q_{hj} + D_j$.

Part 2: The representative consumer in country j spends a fraction γ^U_{gj} of E_j on g and a fraction $\pi_{gi,j}$ of $\gamma^U_{gj}E_j$ on g sourced from i. Thus, the country j consumer spends $\pi_{gi,j}\gamma^U_{gj}E_j$ on (g, i). Substituting in the part 1 expression for E_j, the country j consumer spends $\pi_{gi,j}\gamma^U_{gj}(\sum_h \gamma^V_{hj}Q_{hj} + D_j)$ on (g, i).

Part 3: Country j producers of h have sales and hence costs of Q_{hj}. A fraction $\gamma^I_{g,hj}$ of Q_{hj} is spent on input g and a fraction $\pi_{gi,j}$ of $\gamma^I_{g,hj}Q_{hj}$ is spent on g sourced from i. Since country j producers of h spend $\pi_{gi,j}\gamma^I_{g,hj}Q_{hj}$ on (g, i), country j producers together spend $\sum_h \pi_{gi,j}\gamma^I_{g,hj}Q_{hj}$ on (g, i).

Part 4: Collecting the conclusions of parts 2 and 3, country j consumer and producer expenditures on (g, i) are

$$E_{gi,j} = \sum_h \pi_{gi,j}\gamma^I_{g,hj}Q_{hj} + \pi_{gi,j}\gamma^U_{gj}\left(\sum_h \gamma^V_{hj}Q_{hj} + D_j\right)$$

Eq. (8) follows immediately. □

Appendix B. Primary factor input demands

Proof of Eq. (10). By Shephard's lemma, ω_g's per unit demand for primary factor f is just the derivative of the unit cost function i.e., the derivative of $c_{gi}/z_{gi}(\omega_g)$. Hence ω_g's total demand for f is $V_{fgi}(\omega_g) \equiv \{\partial[c_{gi}/z_{gi}(\omega_g)]/\partial w_{fi}\}q_{gi}(\omega_g)$. Rearranging, $V_{fgi}(\omega_g) = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1}\{[c_{gi}/z_{gi}(\omega_g)]q_{gi}(\omega_g)\}$. Integrating this over ω_g generates demand for f by all varieties in gi, $V_{fgi} \equiv \int V_{fgi}(\omega_g)d\omega_g = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1} \int [c_{gi}/z_{gi}(\omega_g)]q_{gi}(\omega_g)d\omega_g$. But the integral is just sales Q_{gi}. Hence, $V_{fgi} = [\partial c_{gi}/\partial w_{fi}](c_{gi})^{-1}Q_{gi}$. Hence demand for f by all varieties in (g, i) per dollar of sales of (g, i) is $d_{fgi} \equiv V_{fgi}/Q_{gi} = [\partial c_{gi}/\partial w_{fi}]/c_{gi}$. From the unit cost functions (Eqs. (1) and (5)), $[\partial c_{gi}/\partial w_{fi}]/c_{gi} = [\partial c^V_{gi}/\partial w_{fi}]/c^V_{gi}$. Using Eq. (1) to calculate $[\partial c^V_{gi}/\partial w_{fi}]/c^V_{gi}$ yields Eq. (10). □

Appendix C. List of countries and industries:

C.1. List of Countries:

We include the following 39 countries from the 2013 vintage of the WIOD data base: Australia[5], Austria[1,2,3], Belgium[1,2,3], Brazil, Bulgaria, Canada[4], China[6,8], Cyprus[1,2,3], Czech Republic[1,2,3], Denmark[1,2,3], Estonia[1,2,3], Finland[1,2,3], France[1,2,3], Germany[1,2,3], Great Britain[1,2,3], Greece[1,2,3], Hungary[1,2,3], India[6], Indonesia[8], Ireland[1,2,3], Italy[1,2,3], Japan[7], Korea, Latvia[1,2,3], Lithuania[1,2,3], Malta[1,2,3], Mexico[2,4,7], Netherlands[1,2,3], Poland[1,2,3], Portugal[1,2,3], Romania, Russia, Slovakia[1,2,3], Slovenia[1,2,3], Spain[1,2,3] Sweden, Taiwan, Turkey[3], and USA[4,5].

There is a EU customs union that takes a value of one for trade between the following countries and zero otherwise: Austria, Belgium, Cyprus, Czech Republic, Denmark, Germany, Spain, Estonia, Finland, France, Great Britain, Greece, Hungary, Ireland, Italy, Lithuania, Latvia, Malta, The Netherlands, Poland, Portugal, Slovakia, Slovenia.

There is another but single dummy that takes a value of one if two countries are both members of a preferential trade agreement in 2006. Membership is represented by the following superscripts above the country names as follows: (1): The European Union, (2): the EU-Mexico Trade Agreement, (3): the EU-Turkey Trade Agreement, (4): NAFTA, (5): the Australia-United States Trade Agreement, (6): the China-India Trade Agreement, (7): the Japan-Mexico Trade Agreement, (8): the China-Indonesia Trade Agreement.

[31] Recall that all the γs in this paper are Cobb-Douglas exponents.

We do not use Luxembourg in our analysis because it does not report any production in some industries and because its economy is highly distorted by its tax-haven policies. We also dropped the rest of the world because it was not obvious how to calculate objects such as bilateral distance.

C.2. List of Industries and NACE codes:

We use the following industries: Agriculture (AtB); Mining (C); Food, Beverages, Tobacco (15t16); Textiles and Textile Products (17t18); Leather and Footwear (19); Wood and Products of Wood (20); Pulp, Paper, Printing, and Publishing (21t22); Coke, Refined Petroleum, and Nuclear Fuel (23); Chemicals (24); Rubber and Plastics (25); Non-Metallic Minerals (26); Basic and Fabricated Metals (27t28); Machinery, nec. (29); Electrical and Optical Equipment (30t33);Transport Equipment (34t35); Manufacturing, nec. (36t37); Electricity, Gas, Water Supply (E); Construction (F); Wholesale and Retail Trade (50,51,52); Hotels and Restaurants (H); Transport (60,61,62,63,64); Finance, Insurance, Real Estate (J,70,71t74); Government Services (L,M,N,O,P). Relative to the WIOD data base, we aggregated up slightly to make our results comparable to previous HOV (Davis and Weinstein, 2001) and more recent Ricardian (Caliendo and Parro, 2015) study. Unlike Caliendo and Parro (2015) and Levchenko and Zhang (2016), we allow for services that are traded subject to iceberg costs that are allowed to differ from manufacturing. For comparability to older papers that also allow for services trade (e.g. Davis and Weinstein, 2001 pg. 1446, Trefler and Zhu (2010) pg. 204), we aggregate certain services. Specifically, we aggregate "Sale, Maintenance, and Repair of Motor Vehicles", "Wholesale Trade", and "Retail Trade" into "Wholesale and Retail Trade." We also aggregate "Inland Transport", "Water Transport", "Air Transport", and "Other Supporting and Auxiliary Transport Activities" into "Transport"; "Financial Intermediation", "Real Estate Activities", and "Renting of Machinery and Equipment and Other Business Activities" into "FIRE"; and "Public Admin", "Education", "Health and Social Work", and "Other Community, Social, and Personal Services" into "Government Services." We drop "Private Households with Employed Persons."

Appendix D. Details of calibration and simulation

1. Calibration of the Productivity Parameters λ^V_{fi} and λ^R_{gi}: If the γ^V_{gi} and $\gamma^I_{h,gi}$ were independent of i then we could follow Levchenko and Zhang (2012) in using the estimates of $c_{gi}/c_{g,\text{us}}$ to solve for the $\lambda^R_{gi}/\lambda^R_{g,us}$. Instead, we appeal to the following generalization of their approach.

Lemma 1.

$$\left(\frac{\lambda^R_{gi}}{\lambda^R_{gus}}\right)^{\frac{1}{\gamma^V_{gi}}}\lambda^V_{Ui} = \left[\frac{c_{gi}}{c_{gus}}\right]^{\frac{-1}{\gamma^V_{gi}}}\left[\left(\frac{\kappa_{gi}}{\kappa_{gus}}\right)^{\frac{1}{\gamma^V_{gi}}}\left(\frac{\{\sum_f \alpha_{fg}(w_{fi}\lambda^V_{Ui}/\lambda^V_{fi})^{1-\sigma}\}^{\frac{1}{1-\sigma}}}{\{\sum_f \alpha_{fg}(w_{fus})^{1-\sigma}\}^{\frac{1}{1-\sigma}}}\right)\prod_{h=1}^{G}\left(\frac{c_{hi}}{c_{hus}}\right)^{\frac{\gamma^I_{h,gi}}{\gamma^V_{gi}}}\right] \prod_{h=1}^{G}\left(\frac{\pi^{1/\theta_h}_{hi,i}}{\pi^{1/\theta_h}_{hus,\text{us}}}\right)^{\frac{\gamma^I_{h,gi}}{\gamma^V_{gi}}}\left(\{\sum_f \alpha_{fg} w^{1-\sigma}_{fus}\}^{\frac{1}{1-\sigma}}\right)^{1-\frac{\gamma^V_{gus}}{\gamma^V_{gi}}} \tag{27}$$

and

$$(\lambda^R_{\text{gus}})^{1/\gamma^V_{\text{gus}}} = \left[(\pi_{\text{gus,us}})^{1/\theta_g}\kappa_g\kappa_{\text{gus}}\right]^{1/\gamma^V_{\text{gus}}}\left[\sum_f \alpha_{fg}(w_{fus})^{1-\sigma}\right]^{1/1-\sigma}. \tag{28}$$

Proof. Plug c^V_{gi} of Eq. (1) into the Eq. (5) expression for c_{gi}. Then divide through by the corresponding expression for c_{gus} to yield

$$\frac{c_{gi}}{c_{\text{gus}}} = \frac{\lambda^R_{\text{gus}}}{\lambda^R_{gi}}\frac{\kappa_{gi}}{\kappa_{g,\text{us}}}\left(\frac{c^V_{gi}}{c^V_{\text{gus}}}\right)^{\gamma^V_{gi}}(c^V_{\text{gus}})^{\gamma^V_{gi}-\gamma^V_{\text{gus}}}\prod_h\left(\frac{P_{hi}}{P_{h,\text{us}}}\right)^{\gamma^I_{h,gi}}\prod_h P^{\gamma^I_{h,gi}-\gamma^I_{h,gus}}_{hus}. \tag{29}$$

Substituting Eq. (7) with $j = i$ into Eq. (6) yields

$$P_{hi} = \kappa_h c_{hi}\pi^{1/\theta_h}_{hi,i}. \tag{30}$$

Hence

$$\frac{P_{hi}}{P_{hus}} = \frac{c_{hi}}{c_{hus}} \frac{\pi_{hi,i}^{1/\theta}}{\pi_{hus,us}^{1/\theta}} \quad . \tag{31}$$

We choose units so that $P_{hus} = 1$.[32] Hence from Eq. (30)

$$c_{gus} = k_g^{-1} \pi_{gus,us}^{-1/\theta} \quad . \tag{32}$$

From Eq. (1) and the fact that $\lambda_{gus}^V = 1$ for $f = S, U$:

$$\frac{c_{gi}^V}{c_{gus}^V} = \frac{1}{\lambda_{Ui}^V} \left(\frac{\sum_f \alpha_{fg} \left(w_{fi} \lambda_{Ui}^V / \lambda_{fi}^V \right)^{1-\sigma}}{\sum_f \alpha_{fg} \left(w_{fus} \right)^{1-\sigma}} \right)^{1/(1-\sigma)} \quad . \tag{33}$$

Eq. (27) is derived as follows. Into Eq. (29) plug (31), then (33), then $P_{hus} = 1$, and then (32). Rearranging the result yields Eq. (27). To derive Eq. (28), start with (33) and substitute out $c_{g,us}$ using (5) evaluated at $i =$ us. The result is a function of λ_{gus}^R and, after setting $P_{hus} = 1$, can be rearranged to yield Eq. (28). □

We can now explain how we calculate the productivity parameters. We first show that all of the variables on the right side of Eqs. (27) and (28) are known. α_{fg}, w_{fi}, $\pi_{gi,i}$, all of the γs and κ_{gi} are from WIOD. $\theta = 5.03$ and $\rho = 4$ pin down $\kappa_g \equiv \Gamma((1+\theta-\rho)/\theta)^{1/(1-\rho)}$. When $f = U$ we have $\lambda_{Ui}^V/\lambda_{fi}^V = 1$ and when $f = S$ Eq. (15) gives $\lambda_{Ui}^V/\lambda_{fi}^V$. Let $\hat{\delta}_{gi}^{\prime}$ be the estimate of $\delta_{gi} - \delta_{gus}$ in Eq. (13). Then from Eq. (12), $c_{gi}/c_{gus} = \exp(-\hat{\delta}_{gi}^{\prime}/\theta)$. Thus, everything on the right side of Eqs. (27) and (28) are known.

Eqs. (15) and (27) pin down $\lambda_{Si}^V/\lambda_{Ui}^V$ and $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}\lambda_{Ui}^V$, respectively, but not λ_{Si}^V and $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}$. To understand why, note that the λ_{gi}^R and λ_{fi}^V enter the cost function multiplicatively rather than separately. From Eq. (5), they enter as $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}\lambda_{fi}^V$. Absolute advantage therefore pins down the product of the $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}$ and λ_{fi}^V, but not the level of each separately. This is why Eqs. (15) and (27) only pin down $\lambda_{Si}^V/\lambda_{Ui}^V$ and $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}\lambda_{Ui}^V$. Clearly we must normalize either the $(\lambda_{gi}^R)^{1/\gamma_{gi}^V}$ or the λ_{fi}^V. Given our focus on endowments it is convenient to normalize the former. From Eq. (27) a convenient normalization is $\sum_g (Q_{gi}/\sum_{g'} Q_{g'i})(\lambda_{gi}^R/\lambda_{g,us}^R)^{1/\gamma_{gi}^R} = 1$. Applying this normalization by multiplying Eq. (27) through by $Q_{gi}/\sum_{g'} Q_{g'i}$ and summing across g pins down λ_{Ui}^V and hence all of the productivity parameters.

Finally, we relate our approach to Malmberg (2017). Malmberg uses the translog identity based on (Caves et al., 1982). Unfortunately, the assumptions underlying the translog identity are that (1) the cost function must be translog and (2) the first-order translog coefficients must be internationally identical. (1) is not satisfied because CES is not translog.

2. Simulation Algorithm: This section describes our algorithm that solves for all the endogenous variables. The primitives that feed into the algorithm are data on endowments $\{V_{fi}\}_{fi}$ and trade deficits $\{D_i\}_i$, the calibrated $\{\lambda_{fi}^V\}_{fi}$, $\{\lambda_{gi}^R\}_{gi}$, $\{\tau_{gi,j}\}_{gij}$, $\{\gamma_{gi}^U\}_{gi}$, $\{\gamma_{gi}^V\}_{gi}$, and $\{\gamma_{h,gi}^I\}_{hgi}$, and σ, θ, and ρ (from external sources).

1. Consider a $N * K$ matrix of factor prices $\{w_{fi}\}$ up to some normalization which we take to be $w_{Uus} = 1$. Solve for a candidate matrix of c_{gi}^V as in Eq. (1).
2. Guess a matrix of values $\{P_{gi}\}$.
   (a) Given $\{P_{gi}\}$, solve for the matrix of candidate unit costs $\{c_{gi}\}$ using Eq. (5).
   (b) Solve for a new set of prices $\{P_{gi}\}$ using Eq. (6).
   (c) Iterate until the new set of $\{P_{gi}\}$ from part 2b is the same as the guess from part 2.
3. Calculate the expenditure shares consistent with these prices $\pi_{gi,j}$ as in Eq. (7).
4. Calculate aggregate expenditures $E_i = w_{Ui}V_{Ui} + w_{Ui}V_{Ui} + D_i$.
5. Solve for the matrix of $\{Q_{gi}\}$ using Eqs. (8) and (9).
6. Using factor market clearing (11) and Eq. (10), calculate total demand for each factor. If labour demand is too high relative to $\{V_{fi}\}$, adjust relative wages upward. If labour demand is too low relative to $\{V_{fi}\}$, adjust relative wages downward.
7. Iterate on $\{w_{fi}\}$ until labour market clearing holds.

[32] This is a choice of quantity units, not a price normalization. To see this note that in international productivity comparisons each industry must have a productivity normalization. A standard one is $\lambda_{gus}^R = 1$ for each g. This is needed because productivity converts input bundles into output bundles and, since input and output bundles are not measured in the same units (e.g., labour and kilograms), the base level of productivity is not unit free. With our WIOD data, which is measured in U.S. dollars, the choice of units for quantities that is easiest to understand is $P_{gus} = 1$ for each g. That is, a unit quantity of g is the amount needed to produce a dollar of revenue in g. Note that the choice of units $P_{hus} = 1$ is not the same as a normalization of prices. While we impose $P_{gus} = 1$ in the benchmark equilibrium, the P_{gus} are not unity in the counterfactuals i.e., the P_{gus} adjust in equilibrium. We could alternatively impose $\lambda_{gus}^R = 1$ for all g and then work out the implied expressions for the P_{gi} in the benchmark equilibrium.

3. Simulation of World Input-Output Table, Trade, and Consumption: Input-output tables report data that are aggregated up from varieties to goods (industries) and that are in values. Recall that $C_{gi,j}$ is the value of country j's consumption of (g, i), $M_{gi,j}$ is the value of country j's imports of (g, i), X_{gi} is the value of country i's exports of g, and $b_{gi,hj}$ is the value of intermediate purchases of (g, i) per dollar of (h, j) output. The following lemma shows how each of these is aggregated up to the industry level and relates each of these back to primitives of the model. It thus shows how each is simulated.

Lemma 2. *(1)* $C_{gi,j} = \pi_{gi,j}\gamma^U_{gj}\left[\sum_{h=1}^{G}\gamma^V_{hj}Q_{hj} + D_j\right]$ *. (2)* $M_{gi,j} = \pi_{gi,j}\sum_{h=1}^{G}(\gamma^I_{g,hj} + \gamma^U_{gj}\gamma^V_{hj})Q_{hj} + \pi_{gi,j}\gamma^U_{gj}D_j$ *for* $j \neq i$ *. (3)* $X_{gi} = \sum_{j\neq i}M_{gi,j}$ *. (4)* $b_{gi,hj} = \pi_{gi,j}\gamma^I_{g,hj}$ *.*

Proof. : (1) $C_{gi,j}$ is country j's consumption of (g, i). The result follows from part 2 of Appendix A. (2) $M_{gi,j}$ is the value of country j's imports of (g, i), which is just j's expenditures on (g, i) i.e., which is $E_{gi,j}$ of Eq. (8). (3) X_{gi} is country i's exports of g, which is the sum over importers $j \neq i$ of their imports $M_{gi,j}$. (4) $b_{gi,hj}$ is the value of intermediate inputs of (g, i) required per dollar of (h, j) output. From the cost function (Eq. (5)), the production of (g, i) uses $\gamma^I_{h,gi}$ dollars of intermediate input h per dollar of output. Swapping indexes, the production of (h, j) uses $\gamma^I_{g,hj}$ dollars of intermediate input g per dollar of output. A fraction $\pi_{gi,j}$ of this g is sourced from i. Hence, purchases of intermediate (g, i) per dollar of (h, j) output is $\pi_{gi,j}\gamma^I_{g,hj}$. □

To simulate the variables in lemma 2 note that the γs and D_j are primitives and the $\pi_{gi,j}$ and Q_{gi} are from outputted from the simulation algorithm (steps 3 and 5, respectively). Thus, the right-hand side of each of the equations in lemma 2 is known. These equations supply the model-generated values of $b_{gi,hj}$, $M_{gi,j}$, X_{gi}, and $C_{gi,j}$. Part 4 of the lemma endogenizes input-output tables, which is closely related to Caliendo et al. (2017), Antràs and de Gortari (2017) and Antràs and Chor (2019). The endogeneity stems from the fact that the $\pi_{gi,j}$ depend on all prices i.e., on all the w_{fi} and P_{gi}. In addition, we endogenize the primary-input requirements table whose typical element d_{fgi} depends on all of the w_{fi} (Eq. (10)). In Section 9.1 we introduced $\boldsymbol{T}_i = (\boldsymbol{I} - \boldsymbol{B})\boldsymbol{Q}_i - \boldsymbol{C}_i$ (Eq. (23)). $\boldsymbol{Q}_i$, $\boldsymbol{C}_i$, and $\boldsymbol{T}_i$ are the ith columns of

$$Q \equiv \begin{bmatrix} Q_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Q_N \end{bmatrix}, \qquad C \equiv \begin{bmatrix} C_{11} & \cdots & C_{N1} \\ \vdots & \ddots & \vdots \\ C_{1N} & \cdots & C_{NN} \end{bmatrix},$$

$$T \equiv \begin{bmatrix} X_1 & -M_{21} & \cdots & -M_{N1} \\ -M_{12} & X_2 & \cdots & -M_{N2} \\ \vdots & \vdots & \ddots & \vdots \\ -M_{1N} & -M_{2N} & \cdots & X_N \end{bmatrix} \text{ and } B \equiv \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1N} \\ B_{21} & B_{22} & \cdots & B_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ B_{N1} & B_{N2} & \cdots & B_{NN} \end{bmatrix}$$

where $\boldsymbol{Q}_i$, $\boldsymbol{C}_{ij}$, $\boldsymbol{M}_{ij}$, and $\boldsymbol{X}_i$ are $G \times 1$ vectors whose gth elements are Q_{gi}, $C_{gj,i}$, $M_{gj,i}$, and X_{gi}, respectively. $\boldsymbol{B}_{ij}$ is a $G \times G$ matrix whose (g, h)-th element is $b_{gi,hj}$. The dimensions of $\boldsymbol{Q}$, $\boldsymbol{C}$, and $\boldsymbol{T}$ are $NG \times N$ and $\boldsymbol{B}$ is $NG \times NG$. Global value chains are captured by the $\boldsymbol{B}_{ij}$. The related trade flows are in the bilateral world trade flows matrix $\boldsymbol{T}$. The fundamental input-output equation is $\boldsymbol{Q} = \boldsymbol{BQ} + \boldsymbol{C} + \boldsymbol{T}$ or $\boldsymbol{T} = (\boldsymbol{I} - \boldsymbol{B})\boldsymbol{Q} - \boldsymbol{C}$.

4. Model Fit: Fig. A1 illustrates that the model fits the data quite respectably. Each panel is a different endogenous variable of interest and the actual data appear on the vertical axis while the model-generated prediction of that data appears on the horizontal axis. In the first column of panels, the first three rows display, respectively, $\ln w_{Si}/w_{Ui}$, $\ln w_{Si}$ and $\ln w_{Ui}$. The line of best fit is displayed as is its slope (standard error) and R^2. The model almost perfectly captures cross-country differences in skill premia. However, the model also systematically overstates the premium in every country: The best fit line is about 0.4 log points above the diagonal. This illustrates a feature of our calibration: We could bring the line to the diagonal by setting $\sigma = 1.1$; however, external studies rarely estimate such a low value of σ so that we would be overfitting the model by choosing σ to improve our fit. In the second column of panels, the first three rows display, respectively, $\ln d_{Sgi}/d_{Ugi}$, $\ln d_{Sgi}$ and $\ln d_{Ugi}$. The bottom panels plot $\ln Q_{gi}$ and $\ln(\pi_{gi,j}/\pi_{gj,j})$. The points far from the OLS line of best fit tend to be agriculture and mining.

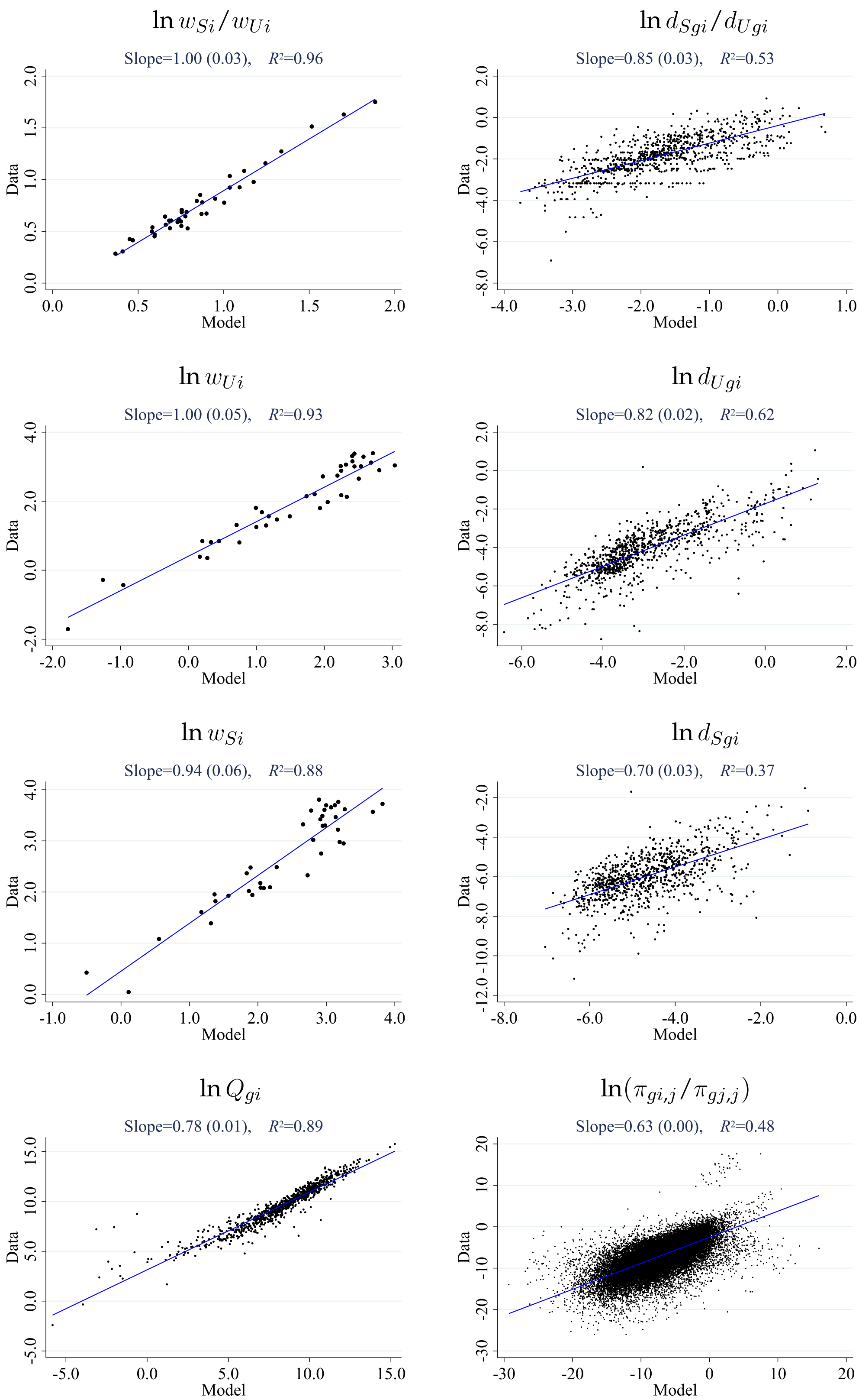

Fig. A1. Model fit.

Appendix E. Proof of Eq. (18):

Proof: The proof starts by totally differentiating $\ln(\sum \widetilde{d}_{Sgi}Q_{gi}) = \ln \widetilde{V}_{Si}$ to obtain

$$\left[\frac{\widetilde{d}_{Sgi}Q_{gi}}{\sum \widetilde{d}_{Sgi}Q_{gi}}\Delta \ln \widetilde{d}_{Sgi} + \frac{\widetilde{d}_{Sgi}Q_{gi}}{\sum \widetilde{d}_{Sgi}Q_{gi}}\Delta \ln Q_{gi}\right] = \Delta \ln \widetilde{V}_{Si} \ .$$

Repeating this for $\ln(\sum \widetilde{d}'_{Sgi}Q'_{gi}) = \ln \widetilde{V}'_{Si}$ and averaging the results yields $\sum_{g=1}^{G}\theta_{Sgi}\Delta \ln Q_{gi} + \sum_{g=1}^{G}\theta_{Sgi}\Delta \ln \widetilde{d}_{Sgi} = \Delta \ln \widetilde{V}_{Si}$. Repeating for $f = U$ and differencing across S and U yields the above. While this is a finite approximation of the derivatives, the approximation is 99.9% accurate. □

Appendix F. Partial equilibrium exercises

Holding wages constant, this exercise solves for unit input requirements $\bar{d}^{D}_{fgi}$ given counterfactual values of λ^{V}_{fi} holding w_{fi} and P_{gi} constant. Where primes denote counterfactual values, unit input requirements can be solved as follows:

$$\bar{d}^{D}_{fgi} \equiv c^{D}_{gi}\left(\gamma^{V}_{gi}/\lambda^{V'}_{fi}\right)\left[\alpha_{fg}\left(w_{fi}/\lambda^{V}_{fi}\right)^{-\sigma}\right]\left[\sum_{f'}\alpha_{f'g}\left(w_{f'i}/\lambda^{V}_{f'i}\right)^{1-\sigma}\right]$$

where

$$c^{D}_{gi} \equiv \frac{\kappa_{gi}}{\lambda^{R}_{gi}}\left\{\left[\sum_{f}\alpha_{fg}\left(w_{fi}/\lambda^{V}_{fi}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}\right\}^{\gamma^{V}_{gi}}\prod_{h=1}^{G}(P_{hi})^{\gamma^{I}_{h,gi}} \ .$$

To solve for the partial equilibrium effect of changes in productivity on dollar input requirements allowing price indexes to change but holding wages constant $\bar{d}^{P}_{fgi}$, we solve for the following system of 2NG equations

$$c'_{gi} = \frac{\kappa_{gi}}{\lambda^{R}_{gi}}\left\{\left[\sum_{f}\alpha_{fg}\left(w_{fi}/\lambda^{V}_{fi}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}\right\}^{\gamma^{V}_{gi}}\prod_{h=1}^{G}\left(P'_{hi}\right)^{\gamma^{I}_{h,gi}} \ .$$

$$P'_{gi} = \kappa_{g}\left[\sum_{j=1}^{N}\left(c'_{gj}\tau_{gj,i}\right)^{-\theta_g}\right]^{-1/\theta_g}$$

holding factor prices constant at their baseline solution. $\bar{d}^{P}_{fgi}$ is then calculated taking these into account.

Appendix G. The vanek equation

Proof of Theorem 1. Pre-multiplying Eq. (23) by $\boldsymbol{A}_f$ yields $\boldsymbol{A}_f\boldsymbol{T} = \boldsymbol{A}_f(\boldsymbol{I}_{NG} - \boldsymbol{B})\boldsymbol{Q} - \boldsymbol{A}_f\boldsymbol{C} = \boldsymbol{D}_f\boldsymbol{Q} - \boldsymbol{A}_f\boldsymbol{C} = \begin{bmatrix} V_{f1} & \cdots & V_{fN}\end{bmatrix} - \boldsymbol{A}_f\boldsymbol{C}$. Consider column i of this equation, namely,

$$\boldsymbol{A}_f\boldsymbol{T}_i = V_{fi} - \boldsymbol{A}_f\boldsymbol{C}_i \tag{34}$$

where $\boldsymbol{T}_i$ and $\boldsymbol{C}_i$ are the ith columns of T and C, respectively. Hence

$$\boldsymbol{A}_f\Sigma_j\boldsymbol{T}_j = \Sigma_j V_{fj} - \boldsymbol{A}_f\Sigma_j\boldsymbol{C}_j. \tag{35}$$

Consider each of the three terms in this equation. $V_{fw} \equiv \Sigma_j V_{fj}$ is the world endowment of f. Recall that $\boldsymbol{T}_j$ is composed of blocks of $G \times 1$ matrices. Let $\boldsymbol{T}_{ij}$ be the ith block of $\boldsymbol{T}_j$. Then by inspection of the definition of $\boldsymbol{T}$ together with globally balanced trade, $\Sigma_j\boldsymbol{T}_{ij} = \boldsymbol{X}_i - \Sigma_j\boldsymbol{M}_{ji} = \boldsymbol{0}_G$ where $\boldsymbol{0}_G$ is the $G \times 1$ vector of zeros. Hence $\Sigma_j\boldsymbol{T}_j = \boldsymbol{0}_{NG}$ where $\boldsymbol{0}_{NG}$ is the $NG \times 1$ vector of zeros. Recall that $\boldsymbol{C}_W \equiv \sum_j \boldsymbol{C}_j$. Thus, Eq. (35) can be written as $0 = V_{fw} - \boldsymbol{A}_f\boldsymbol{C}_w$ or $0 = s_iV_{fw} - \boldsymbol{A}_f(s_i\boldsymbol{C}_w)$. Subtracting this from Eq. (34) yields $F_{fi} = V_{fi} - s_iV_{fw} - \boldsymbol{A}_f(\boldsymbol{C}_i - s_i\boldsymbol{C}_w)$. □

Proof of Corollary 1. For notational simplicity normalize world expenditures to unity so that s_j is j's total expenditures. γ^U_{gj} is the fraction of j's final consumption expenditure allocated to g. $\gamma^U_{gj}s_j$ is what j spends on final consumption of g. $\pi_{gi,j}\gamma^U_{gj}s_j$ is what j spends on final consumption of (g, i). Hence $C_{gi,j} = \pi_{gi,j}\gamma^U_{gj}s_j$. Internationally identical preferences means that $\gamma^U_{gj} = \gamma^U_g$ for all g and j. Zero trade costs means $\tau_{gi,j} = 1$ for all (g, i) and j and so implies that $\pi_{gi,j}$ is constant across all j for a given (g, i) (see Eq. (7)). Call this π_{gi}. Hence, $C_{gi,j} = \pi_{gi}\gamma^U_g s_j$. Summing this over j and using $\sum_j s_j = 1$ yields $C_{gi,w} = \pi_{gi}\gamma^U_g$ so that $s_jC_{gi,w} = \pi_{gi}\gamma^U_g s_j$. This establishes $C_{gi,j} = s_jC_{gi,w}$ or, in matrix notation, $\boldsymbol{C}_j = s_j\boldsymbol{C}_w$. Hence $\boldsymbol{A}_f(\boldsymbol{C}_i - s_i\boldsymbol{C}_w) = 0$. $F_{fi} = V_{fi} - s_i\sum_j V_{fj}$ follows from Eq. (25). □

Appendix H. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jinteco.2022.103620.

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