Quantifying the "Pollution Haven": an Existing Effect but an Unsupported Hypothesis

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Abstract

We develop a full-fledged general equilibrium trade model with pollution as a by-product of production to study the interaction between international trade and pollution emissions. Our quantitative evaluation based on the model suggests that even in the presence of support for the existence of the *pollution haven effect*, the *pollution haven hypothesis* is still unsupported. The reason is that environmental policy stringency, being a crucial determinant of pollution emissions and abatement, is relatively weak in determining international specialization. By comparing environmental policy stringency with other comparative advantage forces one by one, we identify productivity and trade costs to be the major forces that suppress the *pollution haven effect*, which leads to the failure of the *pollution haven hypothesis*. In addition, a reduction in trade costs would induce more worldwide pollution.

Keywords: Pollution haven; Environment and trade; Quantitative trade

JEL Codes: F17, F64, H23, Q56

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1 Introduction

The *pollution haven* is a concept at the center of the research that links international trade and the environment. The two most related economic topics pertaining to it are the *pollution haven hypothesis* (PHH) and its prerequisite, the *pollution haven effect* (PHE). Specifically, the PHE states that the stringency of a country's environmental regulations translates into its comparative advantage, while the PHH posits that a reduction in trade costs causes pollution-intensive sectors to concentrate in countries with relatively weak environmental regulation.

The existing empirical literature has in general established the existence of the PHE but has found no clear evidence to support the PHH (Copeland and Taylor, 2003, 2004; Levinson, 2009; Cherniwchan et al., 2017). This is surprising, as the PHH constitutes a natural extension of the PHE, and thus, it "remains an open question" whether these seemingly contradictory findings can be reconciled (Cherniwchan et al., 2017). In this paper, we intend to answer this question by implementing quantitative exercises on a full-fledged general equilibrium trade model with pollution emissions and multiple determinants of trade patterns such as productivity, trade costs, factor endowments, and input-output linkage. Our method enables an examination of the relative strengths of comparative advantage forces by capturing general equilibrium effects and answer the "what if" questions, with the PHH statement being a typical one in nature, by running counterfactual exercises under certain hypothetical changes in trade costs or environment regulations.

We embed the classic setup of production with pollution emissions as in Copeland and Taylor (2003) into a Ricardian trade model. The trade block of our framework is a multi-country, multi-sector Eaton and Kortum (2002) model with capital and labor as factor inputs as in the classical Heckscher-Ohlin model and input-output linkage and trade in intermediate goods as in Caliendo and Parro (2015). This framework provides a rich set of forces that determine the trade pattern. We discipline the model with the standard parameters in the literature, notably including the trade elasticity governing intensity of trade and the pollution elasticity "governing a firm's trade-off between production and pollution abatement" (Shapiro and Walker, 2018). In addition, we decompose the emissions effect into scale, composition, and technique effects following Grossman and Krueger (1994) and Copeland and Taylor (1994; 1995) to perform a detailed analysis that is comparable to the existing research.

We implement two sets of counterfactual exercises. In the first one, we change the environment regulation stringency by equalizing the sectoral environmental tax rate in all countries to a world average level. By doing this, we are able to confirm the existence and gauge the magnitude of the PHE: the share of dirty sectors'[1] output and total emissions both increase in countries with more stringent regulations, as their environmental tax level is reduced to the world average level, and the opposite effects are found in countries with weak environmental policies. The effects of environmental policies on trade patterns do exist, and their impacts on the environment are clearly much more significant in magnitude, which resembles the findings in Shapiro and Walker (2018). We then execute the second counterfactual exercise to test the PHH by assuming a 20% reduction in trade costs. The outcomes suggest the hypothesis does not hold: dirty industries do not concentrate in countries with lax environmental regulations; instead, their allocation is almost irrelevant to the stringency of environmental regulations. We do find an increase in global emissions, which echoes the prediction of the PHH, but this is a coincidence rather than causality because it is a result of the joint effects of other comparative advantage forces instead of environmental policy stringency.

Theoretically, in the absence of other comparative advantage forces, the PHE should automatically guarantee the PHH. The lack of support for the PHH suggests that there exist other comparative advantage forces that have opposite and stronger effects relative to the PHE, which generates the nonexistence of the PHH in the data. As mentioned above, our model has four other comparative advantage forces in addition to environmental policy: productivity, trade costs, factor endowments, and input-output linkage. For example, following the factor endowment hypothesis as in Antweiler et al. (2001), factor endowment effects (FEE) should run exactly opposite to the PHE, and thus, the PHH would fail under the two counteracting effects.

We implement further quantitative exercises to verify these theoretical conjectures and hunt for the causes of the disparity in findings between the PHE and the PHH. First, we keep the environmental regulation in the model, but exclude the other four forces, and then re-execute the second counterfactual exercise that reduces trade costs. We confirm that the PHE does lead to the PHH in this most simplified baseline scenario. Then, we add the four forces one at a time to the baseline model, and rerun the same counterfactual exercise and compare the results with the baseline scenario. If the results are opposite to the baseline case, this indicates a force that suppresses the PHE; otherwise, it reinforces or is orthogonal to the PHE. We find the evolution of international specialization and pollution are determined primarily by productivity,

[1]We provide a detailed definition of "dirty" in Section 4.

and secondarily by trade costs. These two factors dominate the PHH, with productivity being quantitatively most powerful and with trade costs being relatively less significant in offsetting the PHH.

Our paper contributes to the literature in four different ways. First, we evaluate the interaction of international trade and environment on a global level, with a particular focus on the PHE and the PHH. Existing general equilibrium quantitative analyses based on structural gravity models concerning trade and pollution emissions include Kreickemeier and Richter (2014), Erdogan (2014), and Benarroch and Gaisford (2014). Our paper has three advantages over the existing research. First, we focus on evaluating the PHE and PHH, which provides a unique observation that helps to reconcile the seemingly contradictory empirical findings. Second, the trade part of our framework is a full-fledged trade model incorporating various components, which provides rich possibilities for trade patterns and satisfies our purpose of exploring the relative strength of forces of comparative advantage. Third, the PHH is believed to be a typical issue arising from the North-South trade (Copeland and Taylor, 1994), and therefore, we include both major developed and developing countries in our data. The closest paper to us is Erdogan (2014), but she focuses on pollution effects and negotiations within OECD countries, while we provide a comprehensive examination of the PHH within the most important economies in the world. Similar arguments could also apply to distinguish our paper from another related strand of research linking international trade and carbon dioxide emissions (Hubbard, 2014; Egger and Nigai, 2015; Larch and Wanner, 2017), beyond the fact that our research target is different.

Second, we manage to test the PHH by comparing the strength of different comparative advantage forces, which links our paper to the literature on evaluating sources of comparative advantage. Notably, Chor (2010) assesses the quantitative importance of different comparative advantages in determining trade flows based on an extended Eaton-Kortum model, and he also emphasizes the importance of Ricardian productivity. Our papers share the similarity of comparing the strength of different forces, but he aims to predict trade flow, while we focus on predicting pollution emissions. In addition, our results identify the importance of productivity and trade costs in determining the impacts of trade on the environment. This raises new perspectives for future theoretical and empirical research beyond the factor endowment hypothesis, which the existing research has usually focused on.

Our third contribution is that we provide a flexible and tractable framework to study the relationship between trade and the environment. Our model is one of the new structural gravity models (Costinot and Rodríguez-Clare, 2014). There is another strand of the literature using computational general equilibrium (CGE) models, studying similar issues (for example, Böhringer et al. (2016; 2018) and Nijkamp et al., 2005). As Costinot and Rodríguez-Clare (2014) summarize, there are three main advantages of structural gravity models: (1) they are better micro-founded than CGE models; (2) they offer a close connection between theory and data; (3) they are parsimonious and therefore could present underlying mechanisms. Our quantitative exercises closely connect theory and data, and similar to Larch and Wanner (2017), we also believe the third point helps to explicitly show how pollution emissions change by decomposing the change into the scale, composition, and technique effects.

Last, we provide an updated evaluation of the impacts of trade on the environment. Antweiler et al. (2001) provide an estimate of the impacts of "freer trade" on the environment based on their econometric analysis. This is an important first-step inquiry into the issue, but a general equilibrium quantitative exercise is more suitable for the job. The advantages of our framework also pass on to its results, which better simulate reality and provide some reference to understand the role of trade in determining pollution emissions.

Another close paper to ours is Shapiro and Walker (2018). Based on a two-country Melitz (2003)-style heterogeneous firm model, they quantitatively show that the dramatic decline in US manufacturing pollution emissions is due more to environmental regulations than to changes in productivity and trade. This is a pioneering work in applying structural gravity models to study pollution emissions in the open economy situation with a strong connection between theory and data. Their estimated pollution elasticity facilitates future research, including ours. However, their paper focuses more on the historical evolution of pollution emissions in the U.S., while we are interested in understanding the relationship between international trade and pollution emissions on a global level.

The rest of the paper is organized as follows. Section 2 presents our model. Section 3 describes the data and model calibration. Section 4 discusses the counterfactual analysis and empirical results. With the finding of an unsupported PHH, we find the factors that run against the PHH in section 5, and section 6 checks the robustness of our empirical findings and section 7 concludes.

2 A Quantitative Trade and Environment Model

Consider a world of N countries, indexed by n and i, and of J sectors in each country, indexed by h and j. Firms use labor, capital, and materials from all sectors to produce intermediate goods by a Cobb-Douglas constant-return-to-scale technology. Intermediate goods in all sectors are tradable in a perfectly competitive market, while composite intermediate goods are not tradable. Meanwhile, production in all sectors is accompanied by pollution emissions as a by-product. Firms need to pay environmental tax for pollution but can allocate their resources to pollution abatement. Therefore, each firm chooses the optimal level of pollution abatement and emits pollution.

2.1 Household

In each country, there is a measure of L_n households and of K_n capital. Each household supplies one unit of labor inelastically, and capital is shared evenly across households. A representative household maximizes her utility with the following preference:

$$U\left(C_n\right) = \prod_{j=1}^{J} C_n^{j^{s_n^j}}, \tag{1}$$

where C_n^j is the consumption of final good in sector j, and s_n^j is the consumption weight with $\sum_{j=1}^{J} s_n^j = 1$.

We denote by I_n households' total income, which is derived from two sources. First, households supply labor L_n at a wage rate w_n and rent capital K_n at an interest rate r_n to firms. Second, they receive emissions tax revenues and transfer from the rest of the world on a lump-sum basis. With the Cobb-Douglas formula of preference, it can be shown that the expenditure on goods in sector j is equal to s_n^j share of the total income, i.e., $P_n^j C_n^j = s_n^j I_n$, where P_n^j is the sectoral price index to be defined later.

2.2 Production

Intermediate goods and emissions production

The production of intermediate goods combines two seminal frameworks in trade and environment fields, respectively. Specifically, we follow Copeland and Taylor (2003) in modeling emissions production and abatement technology and Caliendo and Parro (2015) in constructing a global production network in an Eaton-Kortum framework.

There is a continuum of intermediate goods $\omega^j \in [0,1]$ in each sector. Each variety is produced by one firm. A firm makes a two-step decision to produce and sell the intermediate good. In the first step, the firm chooses labor, capital, and materials from all sectors (including its own sector) as inputs to produce intermediate good ω^j, as well as emissions $z_n^j\left(\omega^j\right)$ as a by-product. Following Copeland and Taylor (2003), we call the output in this stage "potential output" and denote it by $y_n^j\left(\omega^j\right)$. The amount of emissions is proportional to the potential output, and is subject to the environmental tax at an exogenous rate t_n^j. In the second step, the firm diverts part of the potential output into pollution abatement, which reduces its pollution emissions and environment tax payable. In other words, the firm makes a decision on the trade-off between higher sales and a lower tax burden to maximize its after-tax profits.

We assume the production of potential output $y_n^j\left(\omega^j\right)$ follows a Cobb-Douglas function:

$$y_n^j\left(\omega^j\right) = A_n^j\left(\omega^j\right)\left[l_n^j\left(\omega^j\right)\right]^{\gamma_{l,n}^j}\left[k_n^j\left(\omega^j\right)\right]^{\gamma_{k,n}^j}\prod_{h=1}^{J}\left[m_n^{h,j}\left(\omega^j\right)\right]^{\gamma_n^{h,j}}, \tag{2}$$

where $A_n^j\left(\omega^j\right)$ is the firm's efficiency in producing intermediate good ω^j; $l_n^j\left(\omega^j\right)$ is labor input; $k_n^j\left(\omega^j\right)$ is capital input; and $m_n^{h,j}\left(\omega^j\right)$ are materials from sector h used to produce a variety in sector j. The parameter $\gamma_n^{h,j} \geq 0$ is the share of expenditure on materials from sector h to produce intermediate good ω^j; $\gamma_{l,n}^j \geq 0$ is the share of the wage bill in the gross output of intermediate good ω^j; and $\gamma_{k,n}^j \geq 0$ is the share of capital investment. Assume $\gamma_{l,n}^j + \gamma_{k,n}^j + \sum_{h=1}^{J}\gamma_n^{h,j} = 1$ for the constant-return-to-scale technology.

After paying the costs of inputs and producing $y_n^j\left(\omega^j\right)$, a firm can allocate a fraction ϵ_n^j of $y_n^j\left(\omega^j\right)$ to emissions abatement activities to reduce its tax payment. The remaining $\left(1-\epsilon_n^j\right)$ fraction is the production of intermediate inputs for sale. We denote the net production after abatement investment by $q_n^j\left(\omega^j\right)$, i.e.,

$$q_n^j\left(\omega^j\right) = (1-\epsilon_n^j)y_n^j\left(\omega^j\right). \tag{3}$$

Moreover, we assume $\epsilon_n^j \in (0,1)$, so firms engage in both abatement investment and sales of intermediate inputs.

Pollution is an increasing function of potential production and a decreasing function of abatement investment. Specifically, we assume the pollution abatement technology to be

$$z_n^j\left(\omega^j\right)=\left(1-\epsilon_n^j\right)^{\frac{1}{\alpha_n^j}} y_n^j\left(\omega^j\right). \tag{4}$$

As Shapiro and Walker (2018) suggest, despite being a specific functional form that satisfies the monotonic requirements with ϵ_n^j and y_n^j, equation (4) corresponds to several equivalent interpretations. It frees us from choosing the interpretation of the nature of pollution in goods production and of a firm's environmental decision, about which the theory and the firm's activities in reality provide few clues. To see this, we solve for $\left(1-\epsilon_n^j\right)$ from equation (4) and plug it into equation (3), along with equation (2), to obtain the net production of intermediate goods as

$$q_n^j\left(\omega^j\right)=\left(A_n^j\left(\omega^j\right)\left[l_n^j\left(\omega^j\right)\right]^{\gamma_{l,n}^j}\left[k_n^j\left(\omega^j\right)\right]^{\gamma_{k,n}^j}\prod_{h=1}^{J}\left[m_n^{h,j}\left(\omega^j\right)\right]^{\gamma_n^{h,j}}\right)^{1-\alpha_n^j}\left[z_n^j\left(\omega^j\right)\right]^{\alpha_n^j}. \tag{5}$$

Hence, the pollution can be equivalently treated as a joint input at the price of tax rate t_n^j.

With the above model assumptions and equivalence, the firm's profit is

$$\Upsilon_n^j \quad = p_n^j\left(\omega^j\right)q_n^j\left(\omega^j\right)-w_n l_n^j\left(\omega^j\right)-r_n k_n^j\left(\omega^j\right)-\textstyle\sum_{h=1}^{J}P_n^h m_n^{h,j}\left(\omega^j\right)-t_n^j z_n^j\left(\omega^j\right). \tag{6}$$

Therefore, the firm's profit maximization problem is to choose $\left\{l_n^j, k_n^j, m_n^{h,j}, z_n^j\right\}$ to maximize profit in equation (6) subject to constraint equation (5). We assume that the market is perfectly competitive, so each firm prices at its unit cost, which equals the cost of production plus the tax payed for emissions. We denote by ψ_n^j the cost of one unit of input bundle:

$$\psi_n^j=\iota_{1,n}^j\left(t_n^j\right)^{\alpha_n^j}\left(c_n^j\right)^{1-\alpha_n^j}, \textit{ where } c_n^j=\iota_{2,n}^j\left(w_n\right)^{\gamma_{l,n}^j}\left(r_n\right)^{\gamma_{k,n}^j}\prod_{h=1}^{J}\left(P_n^h\right)^{\gamma_n^{h,j}}. \tag{7}$$

where c_n^j is the cost paid for one unit of real inputs, and $\iota_{1,n}^j$ and $\iota_{2,n}^j$ are constants.[2] The price of one unit of goods is then the marginal cost ψ_n^j divided by the efficiency of the firm, i.e., $p_n^j\left(\omega^j\right)=\psi_n^j\left[A_n^j\left(\omega^j\right)\right]^{-\left(1-\alpha_n^j\right)}$. Labor and capital are both immobile across countries but freely mobile across sectors within a country, so wage rates and returns to capital are equalized in a country.

Remark. $\alpha_n^j>0$ in equation (4) is an important parameter in our model. It is defined as

[2]Specifically, $\iota_{1,n}^j=\left(\alpha_n^j\right)^{-\alpha_n^j}\left(1-\alpha_n^j\right)^{\alpha_n^j-1}$ and $\iota_{2,n}^j=\left(\gamma_{l,n}^j\right)^{-\gamma_{l,n}^j}\left(\gamma_{k,n}^j\right)^{-\gamma_{k,n}^j}\prod_{h=1}^{J}\left(\gamma_n^{h,j}\right)^{-\gamma_n^{h,j}}$.

the pollution elasticity and shapes both pollution abatement efforts and emissions level. First, to see its definition as pollution elasticity, dividing equation (4) by equation (3) yields

$$\ln\left(\frac{z_n^j\left(\omega^j\right)}{q_n^j\left(\omega^j\right)}\right)=\frac{1-\alpha_n^j}{\alpha_n^j}\ln\left(1-\epsilon_n^j\right).$$

Hence, α_n^j represents the elasticity of pollution intensity to pollution abatement intensity.[3] A lower α_n^j means that pollution intensity is lower with the same abatement effort. In other words, abatement is more efficient and the sector is cleaner in a sector with lower α_n^j.

Second, define emissions intensity $e_n^j\left(\omega^j\right)$ as the ratio of emissions to the value of output, which means $e_n^j\left(\omega^j\right)=z_n^j\left(\omega^j\right)/p_n^j\left(\omega^j\right)q_n^j\left(\omega^j\right)$.[4] According to the Cobb-Douglas production function in equation (5), α_n^j is also the share of pollution compensation in the final output. That is, the environmental tax revenue takes α_n^j share of the total output, i.e. $t_n^j z_n^j\left(\omega^j\right)=\alpha_n^j p_n^j\left(\omega^j\right)q_n^j\left(\omega^j\right)$. Hence, $e_n^j\left(\omega^j\right)=\alpha_n^j/t_n^j\equiv e_n^j$. With α_n^j and e_n^j (pinned down from the production and emissions data), we are then able to infer the implied environmental tax rate t_n^j that characterizes the overall environmental stringency.

The production of composite intermediate goods

Producers of composite intermediate goods in each sector j and each country n purchase intermediate good ω^j from the lowest cost supplier among all countries and then aggregate all the intermediate goods with the CES technology, i.e.,

$$Q_n^j=\left[\int r_n^j\left(\omega^j\right)^{1-1/\sigma^j}\,d\,\omega^j\right]^{\sigma^j/\left(\sigma^j-1\right)}$$

where Q_n^j is the supply of composite intermediate goods; $r_n^j\left(\omega^j\right)$ represents the demand for intermediate good ω^j; and $\sigma^j>0$ is the elasticity of substitution across intermediate goods within sector j. Q_n^j are either used as intermediate inputs in producing intermediate goods $m_n^{j,h}$ or consumed as final goods C_n^j.

We define P_n^j as the unit price of composite intermediate goods:

$$P_n^j=\left[\int p_n^j\left(\omega^j\right)^{1-\sigma^j}\,d\,\omega^j\right]^{\frac{1}{1-\sigma^j}}.$$

[3]We follow Shapiro and Walker (2018) in deriving this property based on equation (4).

[4]An alternative way to define emissions intensity is to use quantity of output rather than value. We choose the current definition mainly for empirical purposes because only trade values are reported in available sector-level international data.

The solution to the aggregate goods producer's problem provides the following demand function of good ω^j

$$r_n^j\left(\omega^j\right)=\left(\frac{p_n^j\left(\omega^j\right)}{P_n^j}\right)^{-\sigma^j}Q_n^j.$$

2.3 International trade and prices

International trade is subject to bilateral iceberg costs κ_{ni}^j. Specifically, $\kappa_{ni}^j>1$ units of intermediate goods have to be shipped from country i to allow for one unit of good to reach country n if $i\neq n$, and $\kappa_{nn}^j=1$. Triangular inequality holds for any three countries, i.e., $\kappa_{nh}^j\kappa_{hi}^j\geq\kappa_{ni}^j$, $\forall\, n,h,i$. Perfect competition ensures that the price paid for an intermediate good is grounded by the minimum unit cost inclusive of the iceberg trade costs, that is,

$$p_n^j\left(\omega^j\right)=\min_i\left\{\frac{\kappa_{ni}^j\psi_i^j}{\left[A_i^j\left(\omega^j\right)\right]^{\left(1-\alpha_n^j\right)}}\right\}.$$

Following Eaton and Kortum (2002), we assume that the effective efficiency of a firm $\left[A_i^j\left(\omega^j\right)\right]^{\left(1-\alpha_n^j\right)}$ in equation (5) follows a Fréchet distribution with location parameter λ_i^j and shape parameter θ^j. Thus, the price of the sectoral aggregate good in sector j in country n is

$$P_n^j=\iota_3^j\left[\sum_{i=1}^N\lambda_i^j\left(\kappa_{ni}^j\psi_i^j\right)^{-\theta^j}\right]^{-\frac{1}{\theta^j}},\tag{8}$$

where $\iota_3^j=\left[\Gamma\left(1+\frac{1-\sigma^j}{\theta^j}\right)\right]^{\frac{1}{1-\sigma_j}}$ is a constant. We assume $\theta^j>\left(\sigma^j-1\right)$ to obtain a well-defined Γ function in ι_3^j.

Since households consume composite intermediate goods at the price P_n^j, with the preference structure in equation (1), the consumption price index in country n is given by

$$P_n=\prod_{j=1}^J\left(P_n^j/s_n^j\right)^{s_n^j}.\tag{9}$$

We denote by X_{ni}^j the expenditure on goods in sector j in country n imported from country i, and by π_{ni}^j the corresponding expenditure share, that is, $\pi_{ni}^j=X_{ni}^j/X_n^j$ and $X_n^j=\sum_{i=1}^N X_{ni}^j$. From the Fréchet distribution, we obtain π_{ni}^j as a function of productivities, costs of production and trade costs

$$\pi_{ni}^j=\frac{\lambda_i^j\left(\kappa_{ni}^j\psi_i^j\right)^{-\theta^j}}{\Phi_n^j},\tag{10}$$

where $\Phi_n^j = \sum_{i'=1}^{N} \lambda_{i'}^j \left(\kappa_{ni'}^j \psi_{i'}^j\right)^{-\theta^j}$. An origin country i that has higher productivity and lower unit costs of goods and trade costs takes a relatively larger share of expenditure in destination country n. Clearly, trade liberalization has an effect on the bilateral expenditure directly through the changes in trade costs κ_{ni}^j, and environmental policies affect trade flows by changing emissions tax t_i^j and then the costs of production ψ_i^j.

2.4 Market clearing and trade balance

Total expenditure on goods in sector j in country n is the summation of the expenditure by firms as materials to produce intermediate goods in all sectors and the consumption by households as final goods, i.e.,

$$X_n^j = \sum_{h=1}^{J} \left(1 - \alpha_n^h\right) \gamma_n^{j,h} \sum_{i=1}^{N} \pi_{in}^h X_i^h + s_n^j I_n, \tag{11}$$

where the household's total income I_n is the summation of labor income, return to capital, transfers from emissions tax revenue and the trade deficit. We denote T_n^j by the emissions tax revenue of sector j in country n; that is, $T_n^j = t_n^j z_n^j$, and $T_n = \sum_{j=1}^{J} T_n^j$ is the total emissions tax revenue of country n. The Cobb-Douglas production function implies $T_n = \sum_{j=1}^{J} \sum_{i=1}^{N} \alpha_n^j \pi_{in}^j X_i^j$. The national deficit is the summation of all sectoral deficits $D_n = \sum_{j=1}^{J} D_n^j$. Hence, the total income I_n is

$$I_n = w_n L_n + r_n K_n + T_n + D_n. \tag{12}$$

The return to capital r_n is determined by the capital market clearing condition in each country:

$$r_n K_n = \sum_{j=1}^{J} \gamma_{k,n}^j \left(1 - \alpha_n^j\right) \sum_{i=1}^{N} \pi_{in}^j X_i^j. \tag{13}$$

Similarly, the wage rate w_n is determined by the labor market clearing condition:

$$w_n L_n = \sum_{j=1}^{J} \gamma_{l,n}^j \left(1 - \alpha_n^j\right) \sum_{i=1}^{N} \pi_{in}^j X_i^j. \tag{14}$$

Plugging the factor market clearing conditions (13), (14) and budget constraints (12) into equation (11) generates the trade balance conditions. Formally, this trade balance is

$$\sum_{j=1}^{J} \sum_{i=1}^{N} X_n^j \pi_{ni}^j - D_n = \sum_{j=1}^{J} \sum_{i=1}^{N} X_i^j \pi_{in}^j. \tag{15}$$

2.5 Equilibrium in level and relative changes

We now complete the model by providing a definition of the equilibrium.

Definition 1 Given a set of fundamentals $\{L_n,\ K_n,\ D_n,\ \lambda_n^j\}$, an equilibrium under a structure of emissions tax policies $\left\{t_n^j\right\}_{j=1,n=1}^{J,N}$ and bilateral trade costs $\left\{\kappa_{ni}^j\right\}_{j=1,n=1,i=1}^{J,N,N}$ is a vector of wages $\mathbf{w} \in \mathbf{R}_{++}^{\mathrm{N}}$, a vector of return to capital $\mathbf{r} \in \mathbf{R}_{++}^{\mathrm{N}}$, and a price matrix $\left\{P_n^j\right\}_{j=1,n=1}^{J,N}$ that satisfy equilibrium conditions (7), (8), (10), (11), (13), and (14) for all j and n.

However, solving the model in Definition 1 under a counterfactual environmental policy or trade costs requires values of a large number of fundamentals and parameters. For simplicity, we adopt the "exact hat algebra" methodology developed by Dekle et al. (2008) in some of our empirical analyses. The idea of the exact hat algebra method is that instead of solving both the current and counterfactual equilibria, we solve the new equilibrium in changes of variables in response to changes of fundamentals and policies. In this way, we are able to directly implement counterfactual analysis without fully calibrating the model.

In the following, we denote by a "hat" variable $\hat{x} = x'/x$ the proportional change of a variable in the counterfactual scenario $\left\{t_n^{j'}, K_n', \lambda_n^{j'}, \kappa_{ni}^{j'}\right\}$ relative to that in the original conditions $\left\{t_n^j, K_n, \lambda_n^j, \kappa_{ni}^j\right\}$. Then, we define the equilibrium in relative changes as follows:

Definition 2 Given $\{L_n,\ D_n\}$, define $\left\{\hat{r}_n, \hat{w}_n, \hat{P}_n^j\right\}_{j=1,n=1}^{J,N}$ as an equilibrium in response to changes in environmental policies, capital endowment, productivity, or trade costs $\left\{\hat{t}_n^j, \hat{K}_n, \hat{\lambda}_n^j, \hat{\kappa}_{ni}^j\right\}$ that satisfy the following conditions, which are the "change" version of Definition 1:

Changes in cost of production

$$\hat{\psi}_n^j = \left(\hat{t}_n^j\right)^{\alpha_n^j} \left[\hat{w}_n^{\gamma_{l,n}^j} \hat{r}_n^{\gamma_{k,n}^j} \prod_{h=1}^{J} \left(\hat{P}_n^h\right)^{\gamma_n^{h,j}}\right]^{1-\alpha_n^j}; \tag{16}$$

Changes in price index

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j \hat{\lambda}_i^j \left(\hat{\kappa}_{ni}^j \hat{\psi}_i^j\right)^{-\theta^j}\right]^{-\frac{1}{\theta^j}}; \tag{17}$$

Changes in bilateral expenditure shares

$$\hat{\pi}_{ni}^j = \hat{\lambda}_i^j \left[\frac{\hat{\kappa}_{ni}^j \hat{\psi}_i^j}{\hat{P}_n^j}\right]^{-\theta^j}; \tag{18}$$

Counterfactual expenditure

$$X_n^{j'} = \sum_{h=1}^{J} \left(1 - \alpha_n^h\right) \gamma_n^{j,h} \sum_{i=1}^{N} \pi_{in}^{h'} X_i^{h'} + s_n^j I_n'; \tag{19}$$

Capital market clearing

$$\hat{r}_n \hat{K}_n r_n K_n = \sum_{j=1}^{J} \gamma_{k,n}^j \left(1 - \alpha_n^j\right) \sum_{i=1}^{N} \pi_{in}^{j'} X_i^{j'}; \tag{20}$$

Labor market clearing

$$\hat{w}_n w_n L_n = \sum_{j=1}^{J} \gamma_{l,n}^j \left(1 - \alpha_n^j\right) \sum_{i=1}^{N} \pi_{in}^{j'} X_i^{j'} \tag{21}$$

where $I_n' = \hat{w}_n w_n L_n + \hat{r}_n \hat{K}_n r_n K_n + \sum_{j=1}^{J} \sum_{i=1}^{N} \alpha_n^j \pi_{in}^{j'} X_i^{j'} + D_n'$.

2.6 Model features and emissions effects decomposition

There are five factors in our model that affect the firm's production decisions and thus affect production specialization, trade flow, and pollution emissions: (1) the factor endowment $\{L_n, K_n\}$. Differences in relative factor endowment result in differences in the relative factor price measured by $\frac{w_n}{r_n}$. This generates the Heckscher-Ohlin force of comparative advantage, along with the fact that productions in different sectors are heterogeneous in factor intensity. Since the capital-intensive sectors also tend to be the pollution-intensive ones, this factor endowment hypothesis is often seen as an alternative to PHH as a theoretical prediction of trade effect on the environment (Antweiler et al., 2001; Levinson and Taylor, 2008). (2) Productivity A_n^j, more specifically, the location parameter λ_i^j and shape parameter θ^j. The productivity gap across countries is economically large and crucial in generating production and trade patterns (Costinot et al., 2011; Levchenko and Zhang, 2016). However, to what extent productivity could further affect pollution emissions is still an open question. (3) Environmental regulation, captured by t_n^j. Its direct effect is stated by the PHE, and the PHH predicts the role it plays during trade liberalization. (4) The trade cost κ_{ni}^j. Trade costs are undoubtedly a strong force in determining international trade and, thus, the production and pollution in a country (Eaton and Kortum, 2002; Anderson and Van Wincoop, 2004). (5) The input-output linkage. It shifts production and trade patterns and directly interacts with the other factors (Grossman and Rossi-Hansberg, 2008; Caliendo and Parro, 2015).

To further understand the pollution effects, we follow Grossman and Krueger (1994) and Copeland and Taylor (1994) in decomposing the trade effect on the environment into scale, composition and technique effects.[5] We also apply the same decomposition in our framework. We denote by $Y_n^j = \sum_{i=1}^N X_{in}^j$ the output of sector j in country n, by $Y_n = \sum_{j=1}^J \sum_{i=1}^N X_{in}^j$ the total output of country n, by $\nu_n^j = \sum_{i=1}^N X_{in}^j / Y_n$ the share of output of sector j in total output in country n, and by $Z = \sum_{n=1}^N Z_n$ the global emissions. Then, national and global emissions can be decomposed as[6]

$$\begin{aligned}
dlnZ_n &= \underbrace{\frac{1}{Z_n}\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,lnY_n}_{Scale\ Effect} + \underbrace{\frac{1}{Z_n}\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,ln\nu_n^j}_{Composition\ Effect} \underbrace{-\frac{1}{Z_n}\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,lnt_n^j}_{Technique\ Effect}, \\
dlnZ &= \underbrace{\frac{1}{Z}\sum_{n=1}^N \left(\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,lnY_n\right)}_{Scale\ Effect} + \underbrace{\frac{1}{Z}\sum_{n=1}^N \left(\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,ln\nu_n^j\right)}_{Composition\ Effect} \underbrace{-\frac{1}{Z}\sum_{n=1}^N \left(\sum_{j=1}^J \frac{\alpha_n^j}{t_n^j}\sum_{i=1}^N X_{in}^j d\,lnt_n^j\right)}_{Technique\ Effect}.
\end{aligned} \tag{22}$$

For the scale effect, $X_{in}^j d\,lnY_n$ is the change in sector j goods that are imported from n to i, and the summation over countries obtain the change in country n's sector j output. As $\frac{\alpha_n^j}{t_n^j}$ is equal to the emissions intensity, the scale effect is simply the emissions intensity multiplied by the output and then aggregated over countries and sectors. The composition effect follows a very similar interpretation, except that it considers the change of output share ν_n^j. The scale and composition effects can be combined together as the effect of changes of all the bilateral expenditures; that is, $d\,lnY_n^j + d\,ln\nu_n^j = \sum_{i=1}^N d\,lnX_{in}^j$. The technique effects reflect the changes in pollution due to a change in emissions intensity e_n^j. In our model, the pollution tax rate determines the emissions intensity, and therefore the technique effect mainly reflects the impacts of environmental regulations.

We consider two counterfactual exercises to examine the PHE and PHH, respectively. First, a change in environmental policy has a direct effect on a firm's pollution and abatement activities and may further indirectly affect its production decision as it changes the cost of production. Specifically, as shown in equation (22), the direct effect is captured by the technique effect, whereas indirect effects are captured by the scale and composition effects as t_n^j affects X_{in}^j. Second, trade costs $\hat{\kappa}_{ni}^j$ interact with all the forces in the model to affect production and trade.

[5]This decomposition approach has been widely used in the literature. See, for example, Antweiler et al. (2001); Levinson (2009); Shapiro and Walker (2018)

[6]Please refer to Appendix B for detailed derivations.

Specifically, changes in trade costs could directly induce the scale and composition effects (i.e., $\hat{\kappa}_{in}^j$ affects X_{in}^j for every $i \neq n$) due to the general equilibrium nature of our model. The debate on the PHH mostly focuses on the composition effect, investigating whether a liberalization shock changes the structure of output in an economy to make it cleaner or dirtier, and how large the effect is. We are interested in the total effects, in relation to the question of whether free trade is good for the environment in each country as well as in the world.

To sum up, with our full-fledged model, we would like to examine the PHE and PHH quantitatively and provide an evaluation of trade and the environment. In the following, we present our data and quantitative methods.

3 Data and Model Calibration

3.1 Data

We first use data on sectoral production and bilateral expenditure from the World Input-Output Table (WIOT) and pollution emissions from the environmental accounts, both obtained from the World Input-Output Database (WIOD).[7] Based on the WIOD data, we are able to calculate the counterparts of bilateral expenditures X_{in}^j, gross output Y_n^j, value-added V_n^j, and emissions z_n^j in the model. We also use the WIOT to calculate the sector linkage parameters $\gamma_n^{h,j}$. Second, to calculate the wage rate, we obtain wage bills from the UNIDO Industrial Statistics Database at the 2-digit level of ISIC (INDSTAT2), and employment data, adjusted by the human capital index, from the Penn World Table (PWT) 8.1 (Feenstra et al., 2015). To calculate returns to capital, we first recover the total payment to capital by total value added less the wage bill and emissions tax revenue (in which total value added comes from the INDSTAT2) and then obtain the capital stock from PWT 8.1.[8] In the robustness check section, we also use the sectoral factor stock data from the WIOD Social Economic Account (SEA). The SEA reports the labor stock, measured by total working hours, and the real capital stock in every sector and every country[9]. Finally, to capture the cross-country differences in abatement elasticities, we obtain the environment-related tax revenue from the OECD Environment Database. We choose the year 2007 for all these data and calibrate our model to the world economy right before the great

[7]We use the 2013 released table to maintain a unified sector classification between the production/expenditure data and the environment accounts.

[8]The capital stock in PWT 8.1 is measured in 2005 US dollars. We use the Producer Price Index in International Financial Statistics (IFS) from the IMF to convert it to 2007 US dollars.

[9]The real capital stock is measured in national currency. We also convert the stock of all the countries into U.S. dollar values with the exchange rate data from the IFS.

trade collapse.

By maximizing the number of countries with high-quality data, we end up with 32 countries and a constructed rest of world. We calibrate the model to 13 manufacturing sectors in these 33 countries.[10] We provide detailed information on the data in Appendix B.

3.2 Model calibration

Trade and pollution elasticity The pollution elasticity α_n^j and the trade elasticity θ^j are two key parameters in our paper. The pollution elasticity determines the firm's decision between production and pollution abatement, and Shapiro and Walker (2018) provide the first estimate of the parameter. Their estimates are at the sectoral level based on US firm-level data. For our purpose, we need the parameter for every country-sector, but unfortunately, we are not able to directly estimate it due to the lack of cross-country firm-level environmental data. Instead, we impute the parameter based on Shapiro and Walker (2018)'s estimates. Specifically, we assume the parameter to be a product of a national component (relative to the U.S. benchmark) and a sectoral component. For the sectoral component, we directly use the estimates for the U.S. from Shapiro and Walker (2018).[11] For the national component, we first calculate each country's average α by dividing the environment-related tax revenue from the OECD environmental data by the gross output in the WIOT and then further divide each country's average α by the U.S.'s average α to calculate to what extent each country deviates from the U.S. benchmark.

We take the sectoral trade elasticities from Caliendo and Parro (2015). Specifically, we use their benchmark estimates for the 99% sample.[12] There are several computational issues when we use these elasticities to calibrate the productivity λ_n^j. First, equation (8) requires that $\theta^j > (\sigma^j - 1)$. We set σ^j to 4, which is the relatively small value acknowledged in the literature. Then,θ^j must be larger than 3. We thus set the values in θ^j that are smaller than 3 to the lowest elasticity that is larger than 3. Second, trade flow is enormously sensitive to prices if the trade elasticity takes extreme values, because it requires large dispersion in productivity to compensate for the difference in marginal cost. In that case, as the wage rate and return to

[10] The sector classification is based on the ISIC Rev.3.

[11] Shapiro and Walker (2018) use the 2016 version of WIOT, but we have to rely on its 2013 version to keep consistent classification with the environmental accounts. Since the classifications in both versions are based on ISIC Rev. 3, most of the sectors in our paper are perfectly comparable with those in Shapiro and Walker (2018). However, there are 7 sectors in Shapiro and Walker (2018)'s classification that correspond to 3 sectors in our data without overlapping. In these cases, we take the simple average value of the α^j into our model.

[12] The industry classification in Caliendo and Parro (2015) is in general consistent with ours, except for 8 sectors that should correspond to 3 sectors in our data. Fortunately, each of these 8 sectors maps to only 1 sector in our data. Therefore, to calculate trade elasticities for these 3 sectors, we simply take the average value of the θ^j from the corresponding sectors.

capital are already modestly dispersed across countries, the dispersion of calibrated productivity would be so wide and exceed the computing range. To prevent such a computation problem, we set the first and second largest values in θ^j to the third largest value. As a robustness check, we also experiment with alternative values of the trade elasticities. Specifically, we set the value of all θ^j to 4, which is the preferred estimate in Simonovska and Waugh (2014).

Production, consumption and trade flows We obtain the bilateral expenditures X_{in}^j, gross output Y_n^j, and value added V_n^j from the WIOT. Then, the expenditure shares are calculated by using the definition $\pi_{in}^j = X_{in}^j / \sum_{i=1}^N X_{in}^j$, and so are the trade deficits $D_n^j = \sum_{i=1}^N X_{ni}^j - \sum_{i=1}^N X_{in}^j$. The production function (5) implies $V_n^j / Y_n^j = \left(\gamma_{l,n}^j + \gamma_{k,n}^j\right)\left(1 - \alpha_n^j\right) + \alpha_n^j$; therefore, we calculate the ratio of value added to gross output V_n^j / Y_n^j, subtract α_n^j and further divide it by $1 - \alpha_n^j$ to obtain $\gamma_{l,n}^j + \gamma_{k,n}^j$. With the labor share we calculate from the INDSTAT2, we are able to obtain $\gamma_{l,n}^j$ and $\gamma_{k,n}^j$. Similarly, we obtain $\gamma_n^{h,j}$ from the WIOT by dividing the intermediate input by the gross output and then scale the summation with respect to h, $\sum_{h=1}^J \gamma_n^{h,j}$, to the value of $1 - \gamma_{l,n}^j - \gamma_{k,n}^j$. To calculate the sectoral share of final consumption s_n^j, we rewrite equation (11) to obtain $s_n^j = \left(Y_n^j + D_n^j - \sum_{k=1}^J \left(1 - \alpha^j\right) \gamma_n^{k,j} Y_n^k\right) / I_n$, where I_n is the summation of national value added and trade deficit, as in (12).

We consider 4 types of pollutants, namely, nitrogen oxides (NO_x), sulfur dioxides (SO_2), carbon monoxides (CO), and non-methane volatile organic compounds ($NMVOC$). The emissions intensity is calculated by the definition $e_n^j = z_n^j / Y_n^j$. Then, the emissions tax rate t_n^j is obtained using the equality $t_n^j = \alpha_n^j / e_n^j$.

Trade costs and productivity In our quantitative exercises on the PHE and PHH, we use "exact hat algebra" following Dekle et al. (2008) and therefore do not need to calculate trade costs and productivity for the purpose of executing counterfactual exercises. However, in Section 5 when we want to compare different forces that generate the disparity between the PHE and PHH, we need to estimate trade costs and productivity. For trade costs, we use the Head and Ries (2001)'s approach, which is a model-independent procedure and captures all sources of trade frictions.

Specifically, we assume $\kappa_{nn}^j = 1$ for every country n and sector j and calibrate κ_{ni}^j. Notice that the gravity equation (10) obtains the following relationship

$$\frac{\pi_{ni}^{j}\pi_{in}^{j}}{\pi_{nn}^{j}\pi_{ii}^{j}} = \left(\kappa_{ni}^{j}\kappa_{in}^{j}\right)^{-\theta^{j}},$$

which cancels out all importer and exporter fixed effects. By assuming symmetric trade costs, the values of trade costs can be directly inferred using trade flow and trade elasticity; formally,

$$\tilde{\kappa}_{ni}^{j} = \tilde{\kappa}_{in}^{j} = \left(\frac{\pi_{ni}^{j}\pi_{in}^{j}}{\pi_{nn}^{j}\pi_{ii}^{j}}\right)^{-\frac{1}{2\theta^{j}}}. \tag{23}$$

The Head and Ries approach puts relatively limited restrictions on parameters and is designed to match trade flow. It captures all the bilateral frictions by canceling out the unilateral terms and is a very comprehensive measure of trade costs: the "trade costs" in this approach include not only the geographic trade costs but any force that could affect bilateral relative trade flows.

Given the trade costs, we calibrate the productivity λ_n^j in each sector to match the value-added distribution in the data. To be more specific, with $\tilde{\kappa}_{ni}^{j}$ and a guess on productivity, we solve the model and obtain the simulated trade flows, output, and value added. We then compare the simulated value-added distribution with the data and adjust our guess of productivity until convergence.

3.3 Solving the model

With all the parameters and original bilateral data, we solve the model using the algorithm presented in Alvarez and Lucas Jr. (2007) and Caliendo and Parro (2015). We briefly summarize the procedure here and explain it in detail in Appendix C. Consider a counterfactual shock captured by any element in the set $\left\{\hat{t}_n^j, \hat{K}_n, \hat{\lambda}_n^j, \hat{\kappa}_{ni}^j\right\}_{j=1,n=1,i=1}^{J,N,N}$. We first guess a vector of changes in wage and capital return $\{\hat{w}_n, \hat{r}_n\}_{n=1}^{N}$. Plugging the guess vector into equilibrium conditions (16) and (17), together with the bilateral expenditure share, we obtain $\left\{\hat{\psi}_n^j\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right), \hat{p}_n^j\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)\right\}_{j=1,n=1}^{J,N}$ by iterating the changes in price. Then, we solve $\pi_{in}^{j'}$ by using condition (18) with the original π_{in}^{j} and the solution of changes of cost and price. Given $\pi_{in}^{j'}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$, α^j, $\gamma_n^{k,j}$, γ_n^j, s_n^j, and original value added, we solve for a $J \times N$ vector whose elements are counterfactual total expenditure $\left\{X_n^{j'}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)\right\}_{j=1,n=1}^{J,N}$ by condition (19). Finally we use $\pi_{in}^{j'}$, $X_n^{j'}$ to check the equilibrium conditions (20) and (21). We adjust our guess of wage and capital return vectors until the factor market clearing conditions hold, and the trade balance conditions automatically hold as well.

4 Pollution Haven Effect and Hypothesis

In this section, we study the PHE and PHH by imposing counterfactual shocks to environmental policies and trade costs. First, to characterize the PHE, we equalize sectoral emissions tax rates in each country to a world average level in a counterfactual equilibrium and investigate how changes in emissions tax rates affect production and emissions patterns. Then, we study the PHH by considering a counterfactual reduction in bilateral trade costs by 20%. In both exercises, we use the exact hat algebra approach based on Definition 2.[13] For the ease of depositing results and facilitating discussion, we classify 13 sectors into two groups (i.e., clean and dirty sectors) according to their pollution-intensity levels calculated from the data. Specifically, we consider the 6 sectors with high pollution intensities as a dirty sector, and the remaining 7 are combined into a clean sector.[14] Similarly, in addition to the results for each country, we show aggregate effects for two groups of countries (based on their inferred environmental tax rates) as well as the whole world. Specifically, there are 11 economies in the group with low national emissions tax rates, with the 22 economies left in the group having high tax rates.[15]

4.1 PHE

To capture the PHE, we consider a counterfactual scenario, in which the sectoral emissions tax rates are equalized across all countries. By doing so, we keep the world effective environmental stringency constant and consider the PHE resulting from the dispersion of environmental stringency. Specifically, we first calculate a world average tax rate for each sector $\bar{t}^j = \sum_{n=1}^{N} z_n^j / \sum_{i=1}^{N} \alpha_i^j Y_i^j$ and set them as the counterfactual tax rates for all countries. Then, we solve for the equilibrium under the proportional change $\hat{t}_n^j = \bar{t}^j / t_n^j$.

The PHE implies a positive relationship between the change in relative scale of the dirty sector (measured as the share of its output to national total output) in a country and its original tax rate. This is because dirty sectors would expand in countries with high t_n^j, as the stringency of their environmental regulations declines to the world average level. Panel A of Figure 1 confirms the PHE, by showing a significant positive relationship between the original emissions tax rate t_n and the resulting changes in the output share of dirty sectors. Table 1 lists the

[13]To deal with the issue of national trade imbalances, we follow a similar procedure as in Dekle et al. (2008), Ossa (2014), and Caliendo and Parro (2015). Specifically, we first start with the model in the base year and solve the counterfactual case imposing balanced trade, that is, $D_n' = 0$. We then use this implied balanced world economy as our benchmark equilibrium.

[14]Please refer to Table 8 in Appendix A for more details on each sector.

[15]The sample economies and respective groups are listed in Appendix A.

Panel A Effects on Share of Dirty Sectors' Output

Panel B Emissions Composition Effects

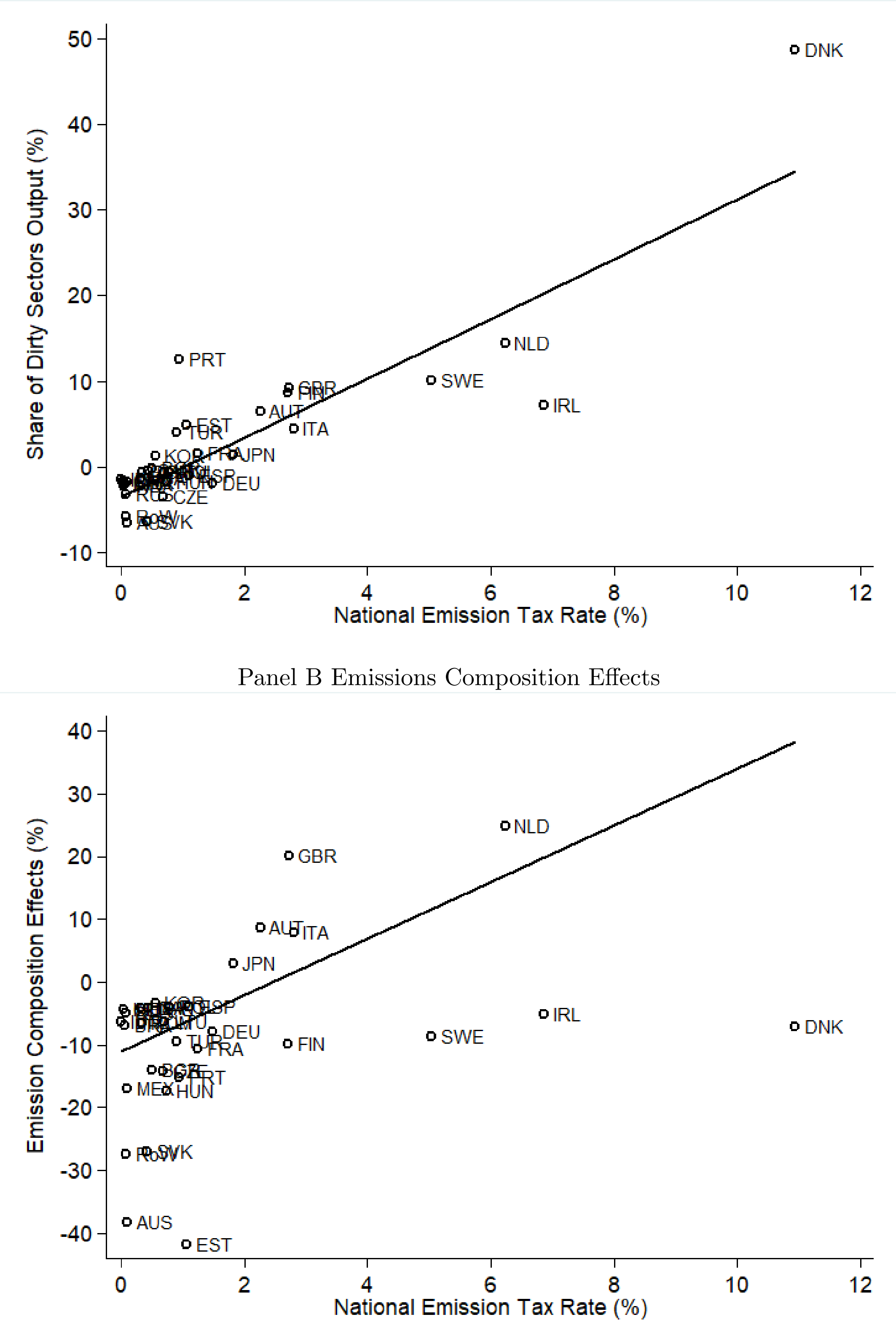


Figure 1: Pollution Haven Effect under Equalized Emissions Tax Rate

Table 1: Pollution Haven Effects under Equalized Emissions Tax Rate

				Decomposition		
Country	Original Tax	Δ Dirty Sector	Emissions Effects	Technique Effects	Scale Effects	Composition Effects
Low t_n	0.075%	-3.19%	-62.96%	-49.77%	6.10%	-19.29%
High t_n	0.899%	2.15%	517.06%	508.86%	11.60%	-3.40%
World	0.192%	-0.04%	19.14%	29.30%	6.88%	-17.04%
Denmark	10.935%	48.72%	25459.24%	25276.21%	190.20%	-7.18%
Ireland	6.862%	7.18%	2490.76%	2479.64%	16.32%	-5.20%
Netherlands	6.232%	14.42%	7469.61%	7398.15%	46.65%	24.82%
Sweden	5.045%	10.10%	2803.89%	2791.89%	20.63%	-8.64%
Italy	2.803%	4.48%	1634.72%	1606.10%	20.77%	7.84%
United Kingdom	2.720%	9.16%	2217.73%	2168.25%	29.47%	20.02%
Finland	2.717%	8.63%	1461.10%	1453.38%	17.64%	-9.92%
Austria	2.260%	6.46%	1326.19%	1299.33%	18.22%	8.64%
Japan	1.821%	1.43%	942.19%	926.52%	12.72%	2.95%
Germany	1.488%	-1.92%	596.45%	592.23%	12.22%	-8.00%
France	1.252%	1.53%	728.64%	726.22%	13.09%	-10.67%
Spain	1.100%	-1.12%	509.13%	500.18%	12.83%	-3.89%
Estonia	1.067%	4.82%	382.05%	411.82%	12.01%	-41.78%
Portugal	0.941%	12.60%	666.26%	660.47%	21.08%	-15.30%
Turkey	0.908%	3.94%	429.12%	421.61%	17.02%	-9.51%
Poland	0.789%	-0.64%	357.79%	349.82%	12.03%	-4.05%
Hungary	0.738%	-1.76%	416.12%	421.90%	11.50%	-17.28%
Lithuania	0.697%	-0.59%	535.61%	528.22%	13.69%	-6.31%
Czech Republic	0.682%	-3.53%	206.61%	210.08%	10.77%	-14.24%
Korea, Republic of	0.556%	1.19%	225.74%	216.46%	12.69%	-3.41%
Bulgaria	0.499%	-0.21%	338.84%	343.89%	8.89%	-13.94%
Canada	0.431%	-0.42%	152.03%	148.27%	7.91%	-4.15%
Slovak Republic	0.422%	-6.38%	117.42%	135.07%	9.43%	-27.08%
Romania	0.332%	-0.66%	106.36%	103.00%	9.93%	-6.57%
United States	0.314%	-1.42%	95.91%	92.57%	7.51%	-4.17%
Australia	0.107%	-6.60%	-43.07%	-5.47%	0.61%	-38.20%
Mexico	0.106%	-1.74%	-40.90%	-31.75%	7.80%	-16.96%
RoW	0.088%	-5.79%	-60.06%	-38.76%	6.21%	-27.51%
Russia	0.077%	-3.29%	-45.51%	-44.29%	3.74%	-4.96%
Brazil	0.060%	-1.89%	-64.20%	-62.84%	5.64%	-7.00%
India	0.043%	-2.21%	-71.96%	-73.50%	5.88%	-4.33%
China	0.041%	-1.61%	-81.74%	-85.31%	7.93%	-4.35%
Indonesia	0.004%	-1.45%	-97.49%	-98.49%	7.35%	-6.35%

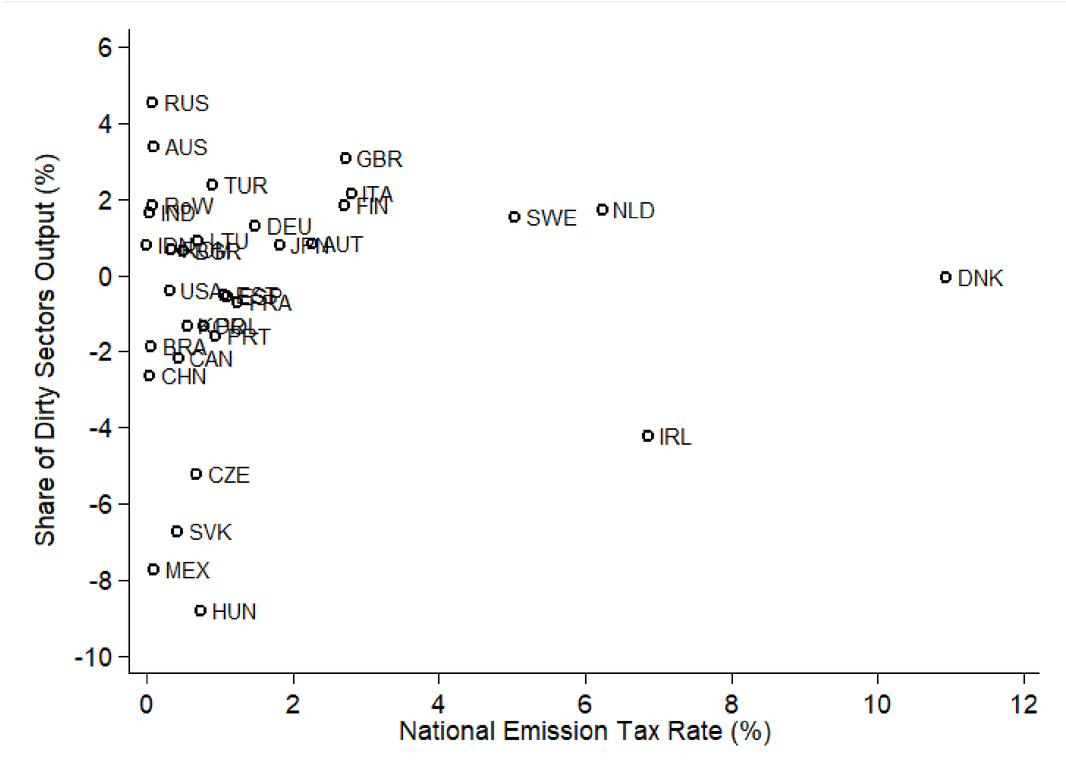
quantitative results of all the countries sorted by their original average tax rate. On average, our mean-reserving counterfactual exercise decreases the relative scale of dirty sectors by 3.19% in countries with low t_n and increases the relative scale by 2.15% in countries with high t_n.

Next, we study the PHE by investigating how environmental policies influence total emissions by changing the output structure. We use the decomposition framework laid out in equation (22) to decompose the total emissions effect into the technique effect, scale effect, and composition effect. The results are listed in Table 1. Panel B of Figure 1 shows the relation of the composition effect in each country with its original tax rate. Similar and consistent results with Panel A are found: a larger increase in emissions is found in countries with higher original taxes, as they experience a larger counterfactual decline in tax rates. Table 1 shows that in aggregation, total emissions decrease by 62.96% as the effective tax rates increase by 156% in countries with low t_n and increase by 517.06% as the effective tax rates decrease by 78.64% in all countries with high t_n.

The regression counterparts of Figure 1 are reported in column (1) of Table 2. They further confirm that the positive relationships uncovered in Figure 1 are statistically significant. Meanwhile, our estimates of the PHE on production and emissions are comparable to those in the literature. For example, Levinson and Taylor (2008) find that an increase in the pollution abatement cost in the U.S. will significantly increase net imports from both Canada and Mexico in over 130 manufacturing sectors, and Hanna (2010) finds the strengthened regulation in the U.S. due to the Clean Air Act Amendments encourages the affected multinational firms to shift their 9% of manufacturing abroad.

The decomposition results in Table 1 further shed light on the underlying mechanisms through which environmental policies influence emissions. We find a substantial technique effect: it accounts for the majority of the total emissions effect in all countries except for Australia.[16] This implies that firms choose to abate less (more) and emit more (less) because emissions becomes cheaper (more expensive). This finding may explain why we find a small production effect of the PHE but a large emissions effect, which is consistent with Shapiro and Walker (2018), who find that a doubled implicit pollution tax primarily drives emissions down in the U.S.

Panel A Effects on Share of Dirty Sectors' Output



Panel B Emissions Composition Effects

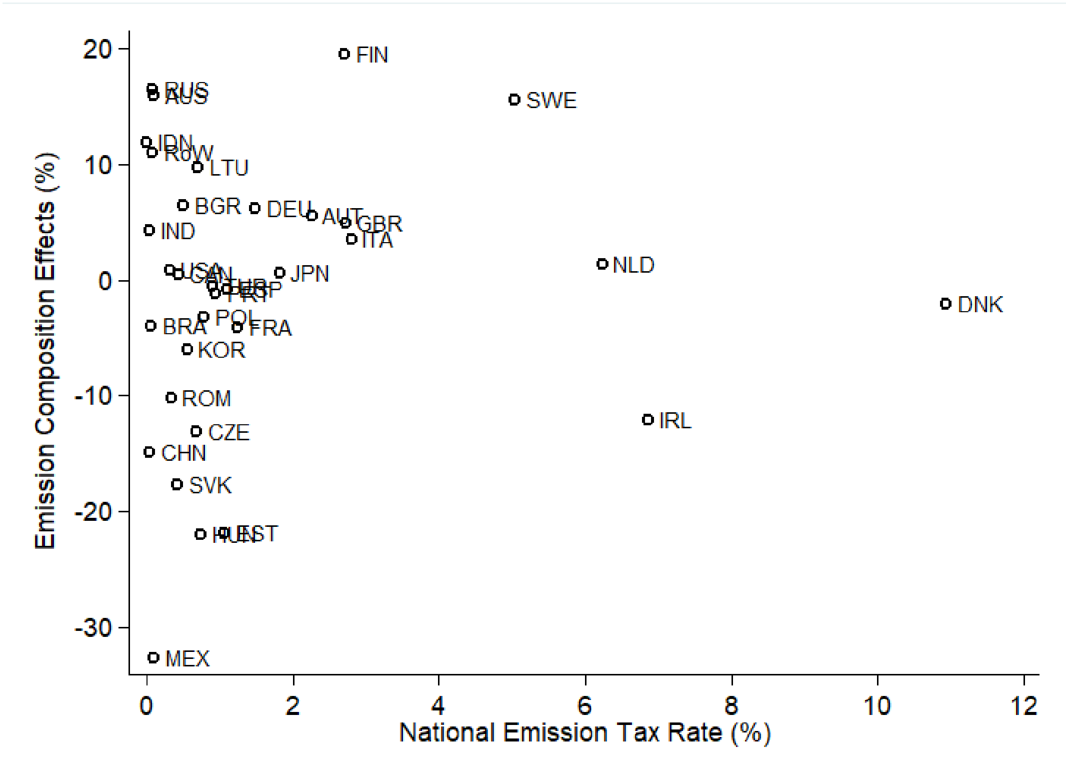


Figure 2: Pollution Haven Hypothesis under Reductions in Trade Costs

Table 2: PHE and PHH Regression

	(1) PHE	(2) PHH	(3) Tax t_n^j	(4) t_n^j+ FEE	(5) t_n^j+ Productivity	(6) t_n^j+ Trade Costs	(7) t_n^j+ IO	(8) No IO
Panel A: Share of Dirty Sectors' Output								
Tax Rate	3.479***	0.299	-0.999**	-0.534**	-0.081	-0.179	-0.965**	-0.104
	(0.543)	(0.246)	(0.379)	(0.220)	(0.066)	(0.363)	(0.392)	(0.367)
R-squared	0.780	0.041	0.317	0.179	0.022	0.011	0.260	0.004
Panel B: Emissions Composition Effects								
Tax Rate	4.514**	0.239	-4.812***	-3.058***	-0.120	-0.329	-4.726**	-1.697
	(2.113)	(0.967)	(1.648)	(0.940)	(0.123)	(1.527)	(1.829)	(2.136)
R-squared	0.264	0.002	0.419	0.361	0.019	0.002	0.279	0.030
Observations	33	33	33	33	33	33	33	33

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

4.2 PHH

The PHH states that trade liberalization causes the dirty sector to expand in countries with weak environmental policies and to contract in countries with stringent environmental policies. To test the PHH, we impose a counterfatual 20% decline in global trade costs and investigate how international trade flow and emissions respond. Specifically, we set $\hat{\kappa}_{ni}^j = 0.8$ if $n \neq i$ and keep all $\hat{\kappa}_{nn}^j = 1$.

In Figure 2, we report the relationship between the original emissions tax rate and the changes in relative scale of the dirty sector in Panel A and the changes of emissions in Panel B, respectively. The PHH predicts significant negative relationships in both figures, which are not supported by the empirical results. The regression results in column (2) of Table 2 further confirm these insignificant relationships. Aggregately, we also find negligible effects in Table 3. Similar to our findings, the PHH is hardly supported in previous studies. For example, Antweiler et al. (2001) find very small composition effects using reduced-form analysis, while Cole and Elliott (2003) even find different signs of the composition effects for different pollutants. Measuring the effect directly from U.S. data, Levinson (2009) finds the composition effects are much smaller than the technique effects and can be explained only to a small extent by international trade.

One possible reason is that there are many important factors other than environmental stringency that contribute to comparative advantage and hence determine the structure of output

[16] In general, countries have some sectors with increases in emissions tax rates and reductions in emissions and have others experiencing the opposite changes. For Australia, the positive and negative changes induced by the tax changes across sectors may cancel out each other, resulting in the aggregately small technique effect.

Table 3: Pollution Haven Hypothesis under Reductions in Trade Costs

				Decomposition	
Country	Original Tax	Δ Dirty Sector	Emissions Effects	Scale Effects	Composition Effects
Low t_n	0.075%	-0.67%	10.17%	5.50%	4.67%
High t_n	0.899%	0.07%	0.76%	0.66%	0.11%
World	0.192%	-0.24%	8.84%	4.81%	4.03%
Denmark	10.935%	-0.05%	5.55%	7.66%	-2.11%
Ireland	6.862%	-4.24%	-5.79%	6.37%	-12.16%
Netherlands	6.232%	1.71%	10.64%	9.24%	1.40%
Sweden	5.045%	1.51%	21.17%	5.63%	15.53%
Italy	2.803%	2.13%	3.12%	-0.43%	3.55%
United Kingdom	2.720%	3.08%	7.47%	2.54%	4.92%
Finland	2.717%	1.84%	26.02%	6.48%	19.54%
Austria	2.260%	0.83%	17.20%	11.69%	5.52%
Japan	1.821%	0.78%	-2.38%	-3.02%	0.64%
Germany	1.488%	1.29%	11.16%	4.93%	6.23%
France	1.252%	-0.72%	-1.18%	2.91%	-4.10%
Spain	1.100%	-0.54%	1.46%	2.27%	-0.81%
Estonia	1.067%	-0.52%	-10.16%	11.68%	-21.84%
Portugal	0.941%	-1.61%	7.97%	9.19%	-1.22%
Turkey	0.908%	2.39%	-0.14%	0.38%	-0.52%
Poland	0.789%	-1.32%	3.68%	6.87%	-3.19%
Hungary	0.738%	-8.82%	-1.20%	20.84%	-22.04%
Lithuania	0.697%	0.90%	21.40%	11.70%	9.70%
Czech Republic	0.682%	-5.21%	7.53%	20.63%	-13.10%
Korea, Republic of	0.556%	-1.34%	-2.57%	3.42%	-5.99%
Bulgaria	0.499%	0.65%	18.79%	12.34%	6.45%
Canada	0.431%	-2.18%	9.12%	8.59%	0.52%
Slovak Republic	0.422%	-6.72%	-0.23%	17.44%	-17.67%
Romania	0.332%	0.67%	-6.58%	3.63%	-10.21%
United States	0.314%	-0.40%	-2.10%	-2.91%	0.81%
Australia	0.107%	3.39%	16.95%	1.02%	15.93%
Mexico	0.106%	-7.72%	-22.06%	10.58%	-32.64%
RoW	0.088%	1.82%	21.58%	10.60%	10.98%
Russia	0.077%	4.55%	15.32%	-1.15%	16.48%
Brazil	0.060%	-1.87%	-8.61%	-4.63%	-3.98%
India	0.043%	1.63%	0.92%	-3.40%	4.32%
China	0.041%	-2.66%	-14.91%	0.04%	-14.95%
Indonesia	0.004%	0.80%	13.07%	1.15%	11.92%

and emissions after trade liberalization (Taylor, 2004). For example, the *factor endowment hypothesis* shown in Antweiler et al. (2001) is a major alternative that generates opposite effects to those of the PHH. As mentioned earlier, there are five elements in our model, including the environmental regulation stringency, that come into play and interact with each other when trade costs decline. To shed light on the failure of the PHH, in the next section, we investigate the strength of each of these other four factors, relative to that of the environmental regulation stringency.

Beyond testing the PHH, we also evaluate the net quantitative effect of trade liberalization on the environment. Table 3 shows that a 20% decline in trade costs increases global emissions by 8.84%, 54.41% of which is explained by the increased output scale. Meanwhile, the composition effect explains the remaining 45.59% of the emissions increase. Our results indicate that, overall, free trade is not good for the global environment.

5 Assessing the Failure of the PHH

We have confirmed the literature findings of the existence of the PHE and the failure of the PHH. In this section, we intend to investigate why the PHH fails in the presence of the PHE. To this end, we start with a benchmark model with only environmental tax and excluding the other three forces of comparative advantage (i.e., factor endowment, productivity, and trade costs) and the effects of input-output linkage. We then add the four forces one at a time to the model and compare their strength with the PHE.

5.1 Benchmark

To have a benchmark model with only the environmental tax in play, we implement the following steps to exclude the other four forces of comparative advantage in the full-fledged model. First, we assume there is no input-output linkage. We implement this by setting the shares of the intermediate goods in production function $\gamma_n^{h,j}$ to 0 and magnify the capital and labor shares proportionally to preserve the constant-return-to-scale technology. Second, to eliminate the factor endowment force, we assume $\gamma_{k,n}^j = \gamma_k^j$ and $\gamma_{l,n}^j = \gamma_l^j$ for each country n, so countries use the same production technology in each sector. Additionally, we impose a change in capital endowment, so all the countries have the same capital-to-labor ratio. With these modifications, the relative returns to labor and to capital $\frac{w_n}{r_n}$ become the same in all the countries. Third, to eliminate the Ricardian productivity force, we impose a set of $\hat{\lambda}_n^j$ so that all countries have the same counterfactual productivity $\lambda_i^{j'}$. Finally, the bilateral trade friction term plays a significant role in shaping international trade (e.g., Anderson and Van Wincoop (2004)). We impose a set of $\hat{\kappa}_{ni}^j$ so that $\kappa_{ni}^{j'}$ equals the average value for any country pair in all sectors, and keep the domestic trade costs $\kappa_{nn}^{j'}$ at 1. We impose all these changes simultaneously, and then the benchmark model features the difference in environmental regulations across countries as the only source of comparative advantage.

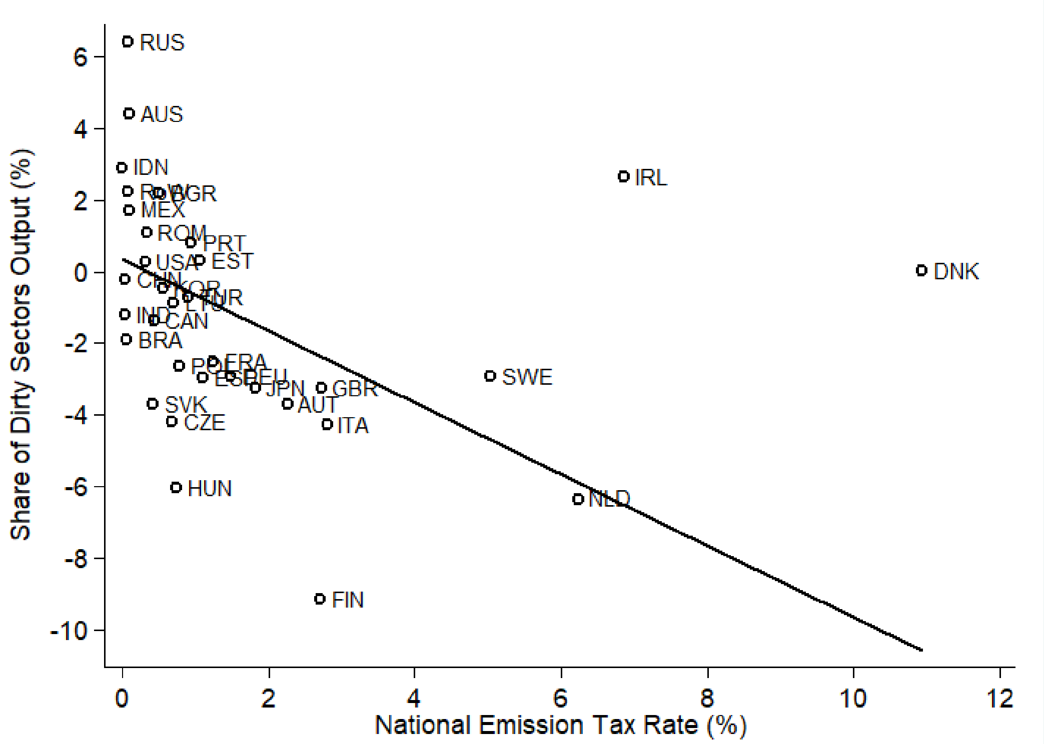
In the absence of other elements that determine the trade pattern, the PHE should imply the PHH. To verify this conjecture, we implement a 20% reduction in trade costs in the benchmark model, the same counterfactual exercise in section 4.2. Figure 3 shows that the effects on the scale of the dirty sector and emissions are both consistent with the prediction of the PHH. Specifically, when trade costs decrease, the dirty sectors expand in countries with low environmental tax rates, and contract in countries with stringent environmental regulations. A similar pattern has been found for emissions. The regression results in column (3) of Table 2 further confirm that these negative relationships are statistically significant. The quantitative effects of the reduction in trade costs in the benchmark model are reported in column (2) of Table 4. For ease of comparison, we copy the effects in the full-fledged model in column (1). Emissions increase by 7.23% in countries with low t_n through the composition effect and decrease by 3.00% in countries with high t_n. The worldwide total emissions increase by 6.84% with the decreased trade costs. The above effects could be considered the pure effects of environmental stringency on the environment through influencing the trade pattern, and they are all quantitatively larger than the net effects in column (1), which suggests that they are partially offset by other forces.

In sum, we confirm the conjecture that when only the environmental regulations are in play, the PHE leads to the PHH. We then examine each of the other four comparative advantages to understand which one offsets the PHE in general equilibrium and leads to the failure of the PHH.

5.2 Factor endowment hypothesis

The factor endowment effect is quantitatively important to international trade (e.g., Romalis (2004) and Chor (2010)) and predicts an opposite effects to the PHE according to the *factor endowment hypothesis* (FEH) in Antweiler et al. (2001). To examine the magnitude of the FEE relative to the PHE, we allow for differences in labor and capital endowment across countries

Panel A Effects on Share of Dirty Sectors' Output



Panel B Emissions Composition Effects

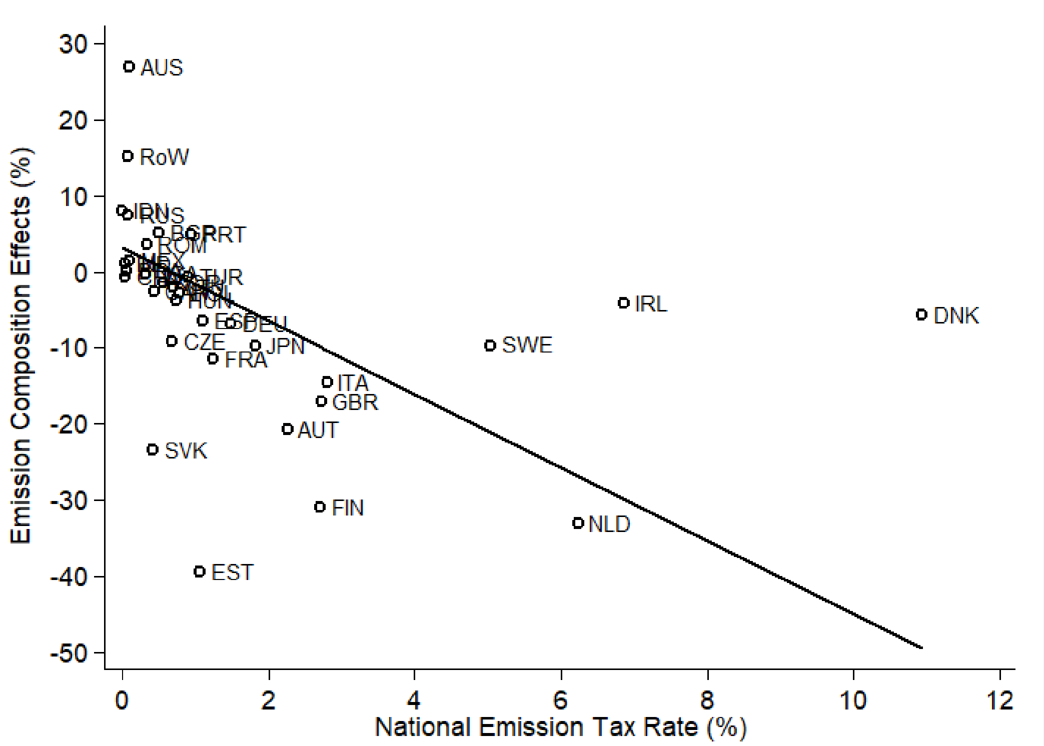


Figure 3: Pollution Haven Hypothesis with Differences Only in Environmental Stringency

and factor intensity in goods production across sectors while excluding the forces of productivity, trade costs, and input-output linkage in the benchmark model. We then impose a 20% reduction in trade costs, and investigate how output structure and emissions changes. The difference between the results in this section and those in section 5.1 indicate the effects of the FEE.

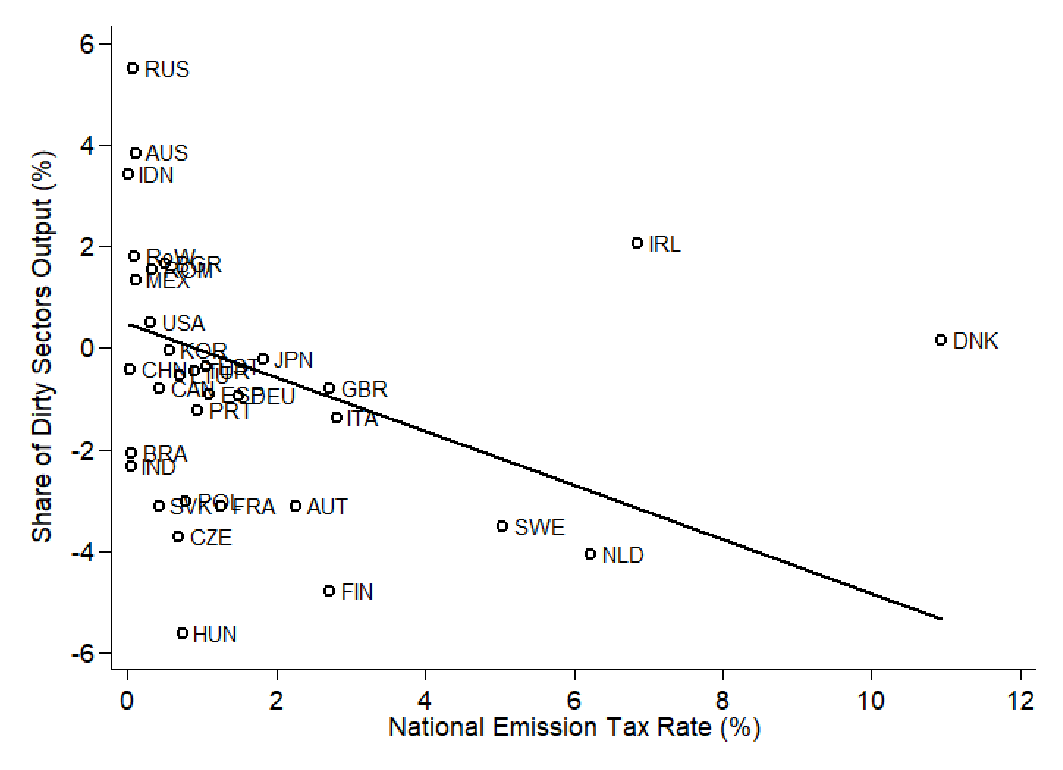
Figure 4 shows the effects on production and emissions. The negative relationships, which are significant, as shown in column (4) of Table 2, indicate that the PHH still holds. Meanwhile, aggregately, we still find significant effects of trade liberalization on production and emissions as in column (3) in Table 4. The effects are quantitatively smaller compared with column (2), especially in the countries with tighter environmental regulation. This suggests that the FEE contrasts with the PHE, but its quantitative power is not strong enough to offset the PHE. Therefore, the PHH pattern remains in this scenario. This finding echoes one of the conclusions in Broner et al. (2012): the quantitative effect of environmental regulation on trade patterns is comparable with the effect of physical and human capital.

5.3 Productivity heterogeneity

Levchenko and Zhang (2016) show that productivity evolution determines country-level growth and trade. Chor (2010) finds that the Ricardian force is significant to welfare. To investigate the role of productivity in this subsection, we add the heterogeneity of sectoral productivity λ_n^j across countries in the benchmark model, controlling for the forces of factor endowment, trade costs and input-output linkage. Again, we impose a 20% reduction in trade costs to reexamine the PHH.

Figure 5 reports the results for production and emissions outcomes. The negative relationships predicted by the PHH disappear. Moreover, the regression results in column (5) of Table 2 indicate the environmental tax has no statistically and economically significant effects on the scale of dirty sectors and emissions. Comparing the quantitative effects in column (4) of Table 4 with those in column (2), we find the aggregate effects drop dramatically after we allow for productivity heterogeneity. For example, emissions effects decrease from 5.20% to 0.38% in countries with low t_n and from -2.39% to -0.63% in countries with high t_n. These results suggest that the effects of productivity heterogeneity cancel out the PHE, leading to the failure of the PHH.

Panel A Effects on Share of Dirty Sectors' Output



Panel B Emissions Composition Effects

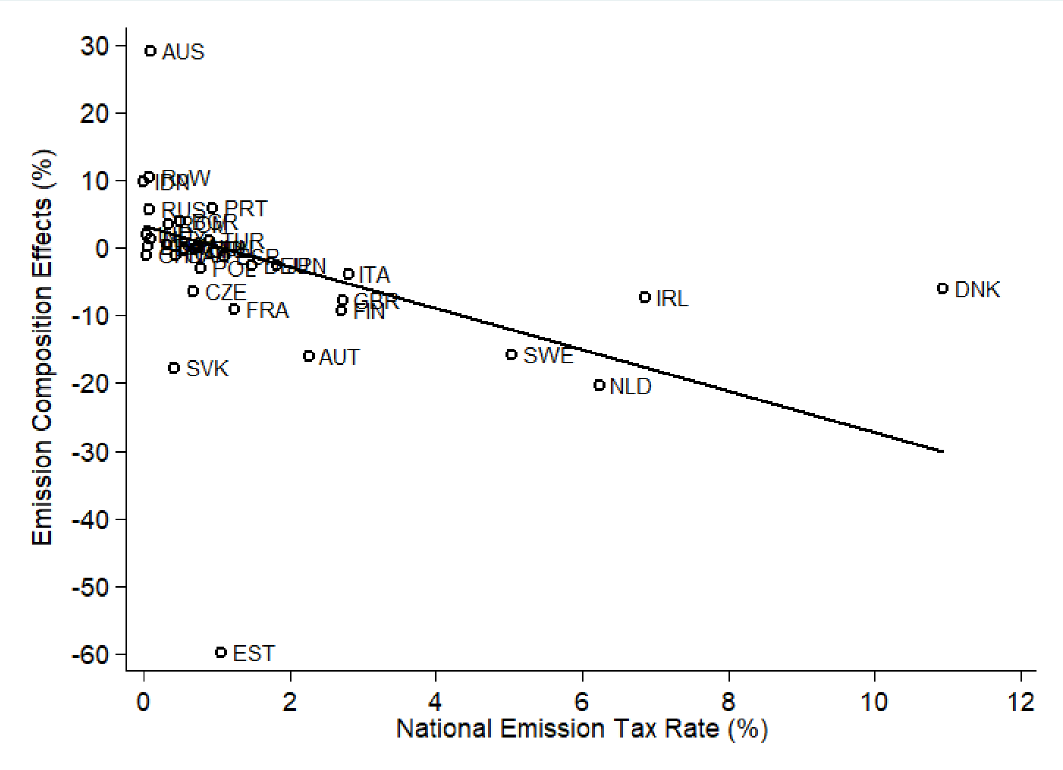
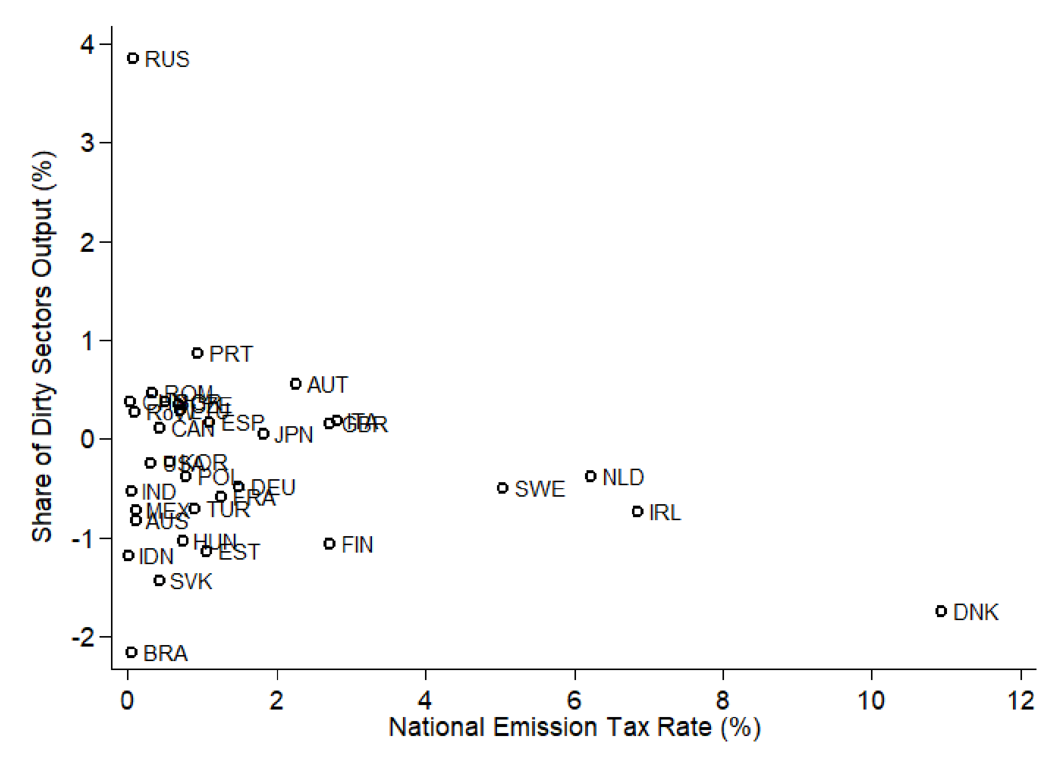


Figure 4: PHH with Differences in Capital-to-Labor Ratio

Panel A Effects on Share of Dirty Sectors Output



Panel B Emission Composition Effects

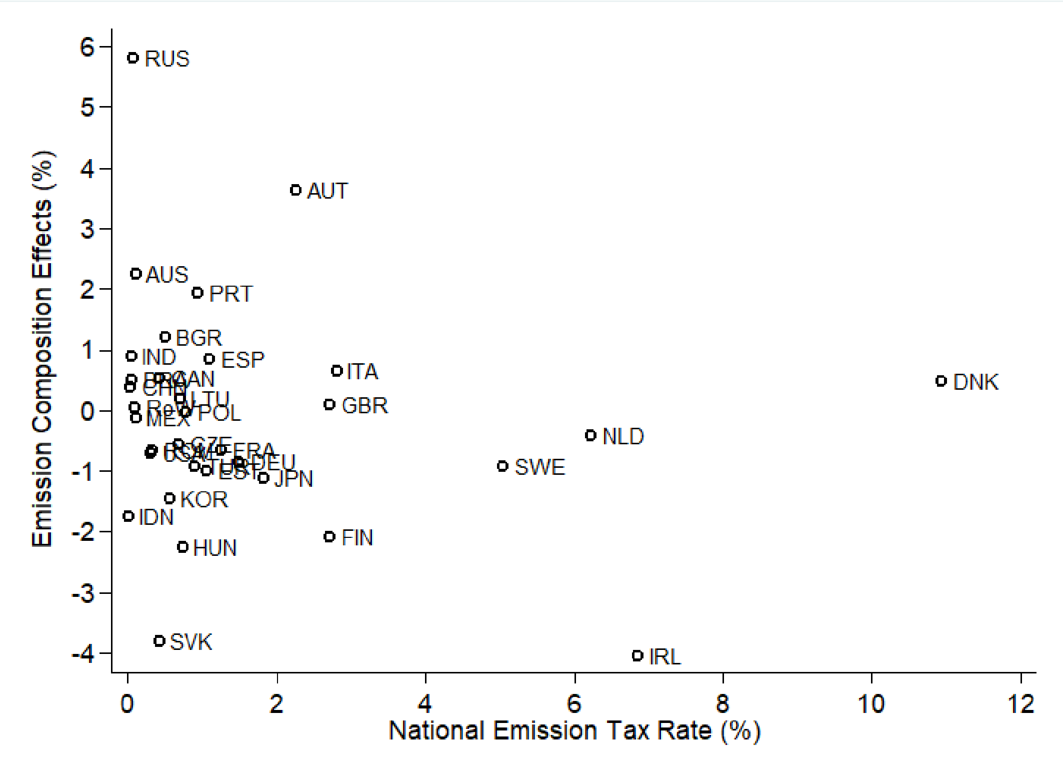


Figure 5: PHH with Differences in Productivity

5.4 Trade costs

As mentioned above, trade costs largely shape the international trade and are probably economically stronger than environmental regulations in determining the trade pattern. In this subsection, we add trade costs back to the model and control for the other three factors. Namely, we only keep the calibrated κ_{ni}^{j} and the original environmental tax rates in the model. Then, we impose a 20% reduction in trade cost, and present the outcome in Figure 6. The negative relationship predicted by the PHH disappears. The regression in column (6) of Table 2 also indicates no significant relationship. Thus, the trade costs completely offset the PHE but do not reverse it to yield the opposite prediction of the PHH. However, when comparing the quantitative effects in column (5) to column (2) of Table 4, we find different effects of trade costs on trade patterns compared with productivity. At the aggregate level, the effects on dirty sectors' output and the composition of emissions are even larger than the effects with only the environmental tax, implying that worldwide production and trade are very sensitive to trade costs. Environmental regulations still plays a role, even though most of its effects are covered by trade costs. Conversely, in the results in subsection 5.3, the effects of productivity are so strong that environmental tax seems to not be effective at all.

5.5 Input-output linkage

The input-output linkage also affects producers' production behavior through the parameters $\gamma_n^{j,h}$. By changing the relative shares of intermediate inputs, it fundamentally reshapes the demand of different country-sectors. In our case, when trade costs decline, they interact with other forces because the effects of any other comparative advantage in one country-sector quickly propagate to other country-sectors not only indirectly through general equilibrium effects but also directly through intermediate input prices. In sum, the input-output linkage alters comparative advantage by changing relative demands and eventually affects trade patterns (Caliendo and Parro, 2015).

In this subsection, we consider two counterfactuals. In the first one, we add back the input-output linkage to the benchmark model by keeping all the $\gamma_n^{j,h}$ and control all other forces. In the second model, we construct a full-fledged model without input-output linkage, i.e., imposing all $\gamma_n^{j,h} = 0$ for any sector j and sector h. We then impose a 20% reduction in trade costs. Note that there is no theoretical guidance on whether the production network would intensify or offset the PHE in the first counterfactual. However, in the second one, it is possible that the

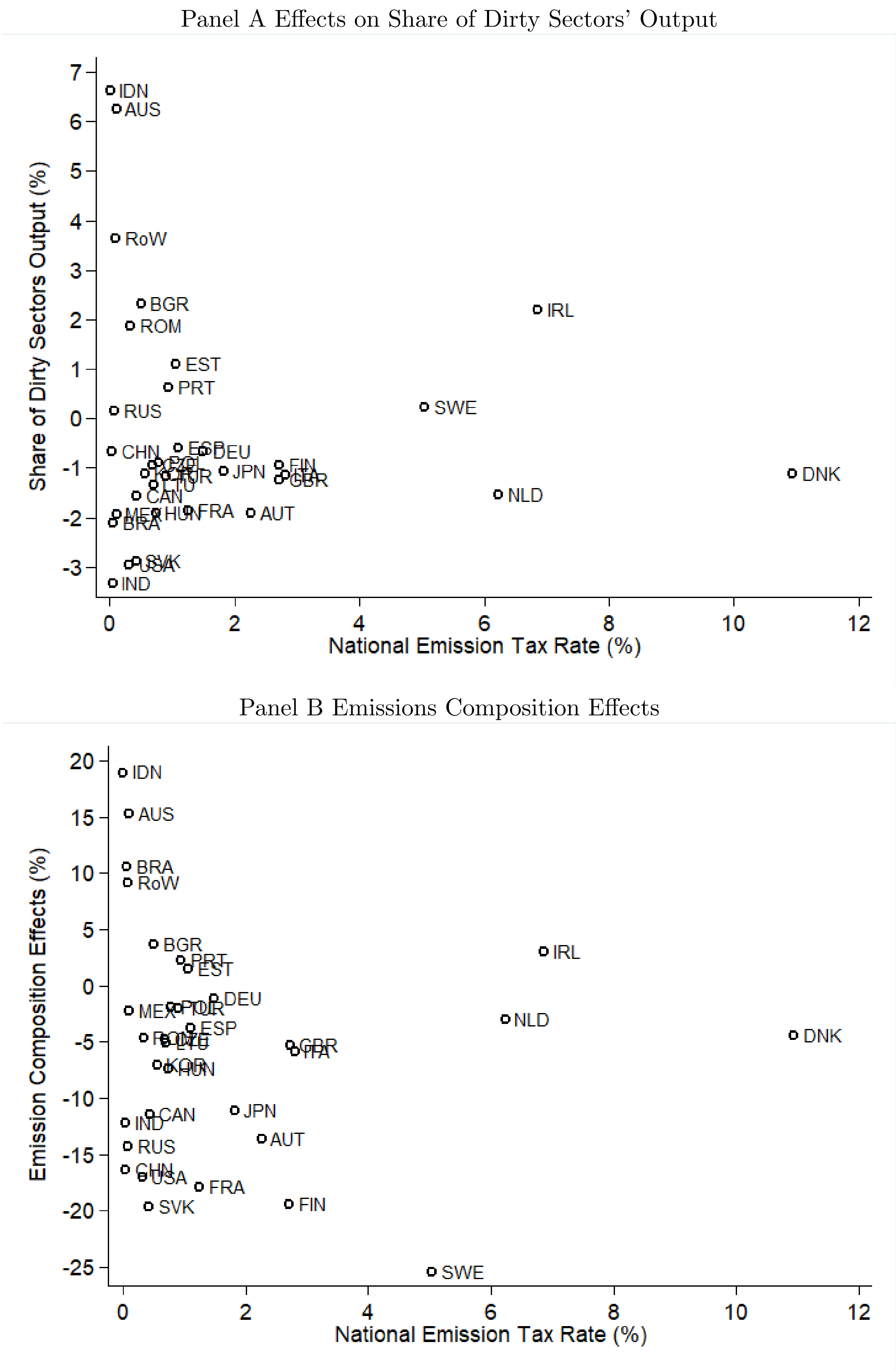


Figure 6: PHH with Differences in Trade Cost

Table 4: Quantitative Comparison of PHH

	(1) PHH	(2) Tax t_n^j	(3) t_n^j+ FEE	(4) t_n^j+ Productivity	(5) t_n^j+ Trade Costs	(6) t_n^j+ IO	(7) No IO
Panel A: Share of Dirty Sectors' Output							
Low t_n	-0.67%	0.64%	0.59%	0.13%	0.77%	0.58%	0.80%
High t_n	0.07%	-1.80%	-0.62%	-0.22%	-1.74%	-2.09%	-0.66%
World	-0.24%	-0.01%	0.01%	0.01%	-0.10%	-0.03%	-0.04%
Panel B: Emissions Composition Effects							
Low t_n	4.67%	7.23%	6.44%	0.38%	5.41%	7.47%	15.89%
High t_n	0.11%	-3.00%	-1.07%	-0.63%	-12.37%	-2.98%	0.26%
World	4.03%	6.84%	5.74%	0.32%	5.15%	7.08%	13.99%

PHH still disappears if productivity and trade costs dominate the trade pattern and suppress the PHE.

We implement these two counterfactuals to serve as a comparison: the second counterfactual includes the interactions with other trade determinants, while the first one excludes the interactions, except for those with the PHE. The effects in the two counterfactuals are illustrated in Figure 7 and Figure 8. The corresponding regression results are reported in column (7) and column (8) of Table 2. The significant negative relationships in Figure 7 and column (7) of Table 2 still support the PHH when the model considers intermediate inputs in production. Comparing the effects in column (6) with column (2) in Table 4, we find no significant difference. Figure 8 and the insignificant relationship in column (8) of Table 2 indicate that when we only eliminate the input-output linkage, the evolution of trade and emissions, determined by all four forces in the model, does not follow the prediction of PHH.

6 Robustness

From the counterfactual analysis, we find evidence for the PHE but no support for the PHH. Moreover, by controlling the comparative advantage forces, we find the effects of productivity are dominant, followed by those of trade costs, while factor endowment is not very powerful. In this section, we check the robustness of these findings. First, our empirical analysis relies on two parameters: emissions elasticity α_n^j and trade elasticity θ^j. To address the concern that the empirical results are parameter-specific, we use alternative values of these two parameters from the literature and rerun all the counterfactual exercises. Second, we further discuss the relationship between the PHE and FEE with an alternative mode of calibration.

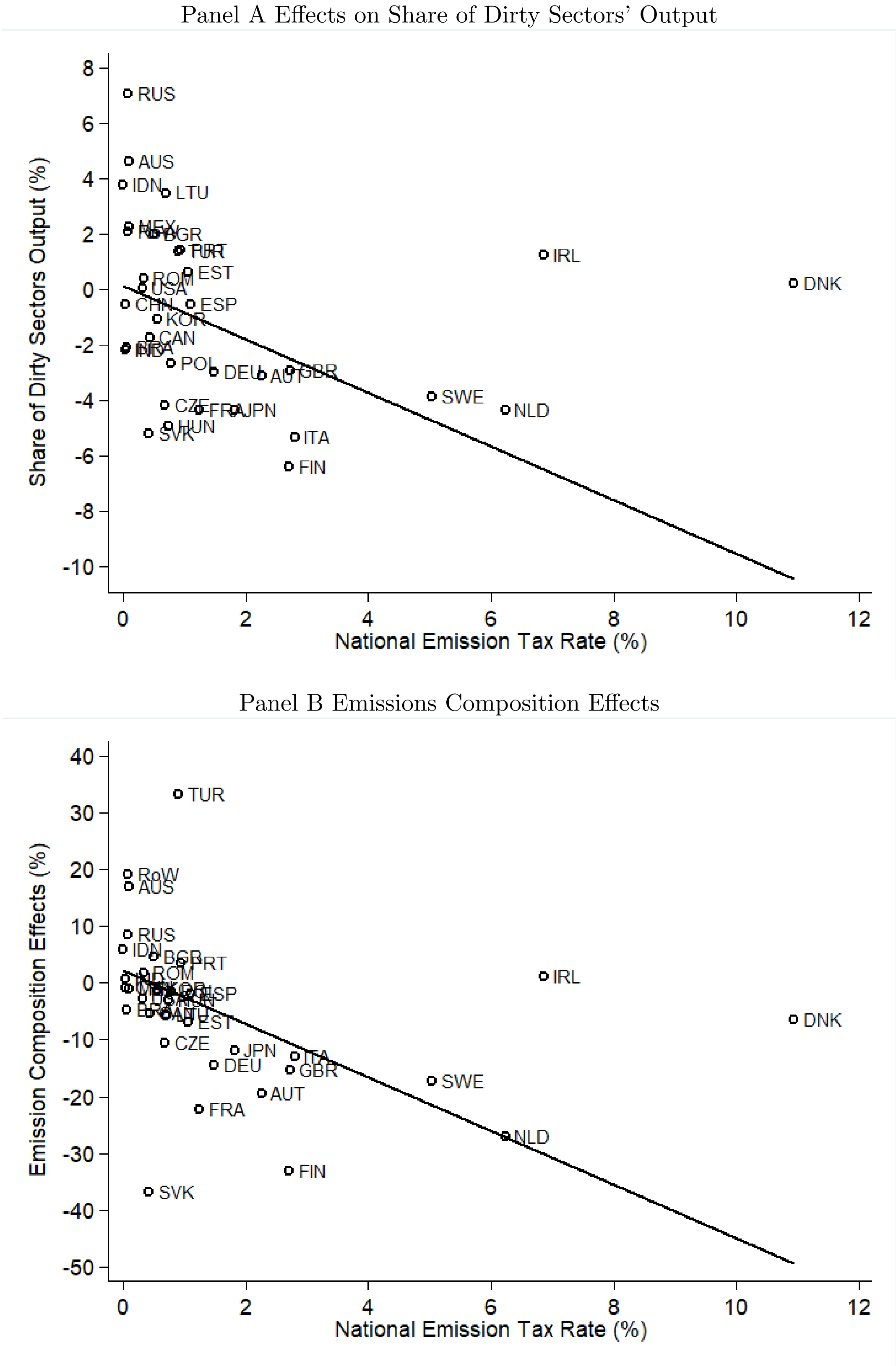


Figure 7: PHH with Differences in Environmental Stringency and Input-Output linkage

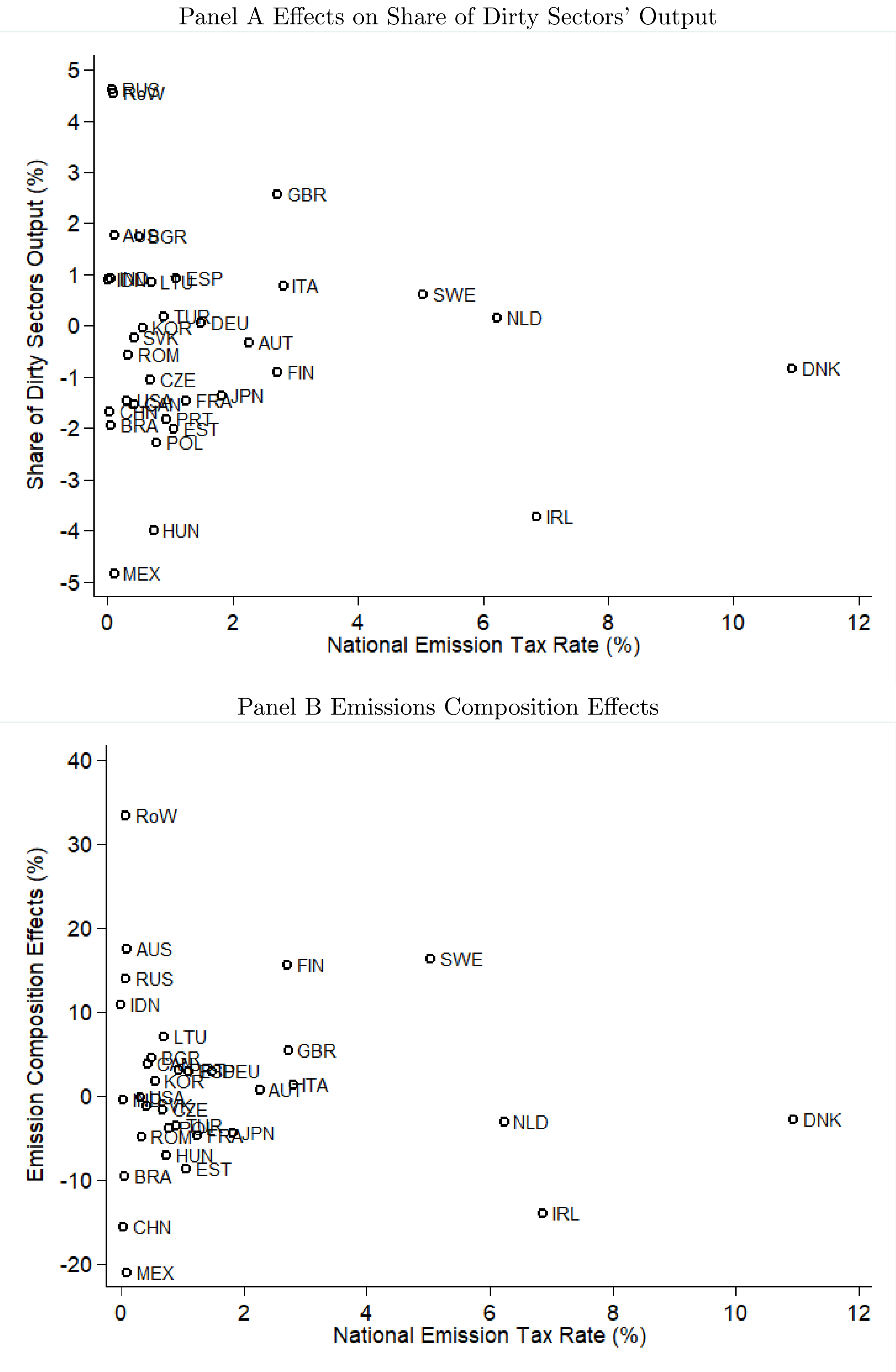


Figure 8: PHH without Input-Output linkage

6.1 Emissions elasticity

The emissions elasticity α_n^j determines the inferred environmental tax and consequently the emissions. Emissions intensity is calculated from production and emissions data, and then, the inferred tax rate is positively determined by α_n^j. Ideally, α_n^j should be directly estimated from micro data. When such data are missing, we impute α_n^j by combining different sources of estimation of α from Shapiro and Walker (2018) and the OECD. In this subsection, we change the values of α_n^j to check whether our findings are robust to the choice of α_n^j.

For each assumption regarding the value of α_n^j, we recalibrate the model and impose the same set of counterfactual exercises as in section 4 and section 5. Table 5 reports the relationship between the environmental tax rate and changes in dirty sectors' output and emissions composition effects when trade costs decline. In the first two panels labeled Model I, we double all the α_n^j. As a result, the implied environmental tax rates are also doubled and thus become more powerful compared with the other comparative advantage forces. Conversely, in Model II, we shrink all the α_n^j by half and report the regression results in the middle two panels. The direct consequence is that the implied environmental tax rates decrease by half, which makes them less powerful in determining the international specialization.

The results in the two cases are consistent with our main findings. The first two columns show an existing PHE but an unsupported PHH. After we eliminate all the comparative advantage forces, the "implicit" PHH still holds. Column (4) suggests the PHH is still valid when adding the factor endowment force into the model. It should be noted that in the latter case, where the environmental regulation force becomes less powerful, the PHH measured by change in production disappears. Thus, the factor endowment force has a certain power to offset the PHE, although it is not economically significant enough to fully crowd out the PHE. Columns (5) and (6) suggest that the productivity and trade cost effects nullify the PHH. Moreover, the productivity is quantitatively more powerful, indicated by the smaller coefficient in column (5). The last two columns confirm the role of the input-output linkage: adding it to the model in section 5.1 enhances the patterns predicted by the PHH, but simply eliminating the linkage does not reveal the PHH.

6.2 Trade elasticity

The trade elasticity θ^j is key to computing the quantitative implications of international trade, but its estimate varies across methods and data. In the benchmark exercise, we use estimated

Table 5: Robustness under different α_n^j

	(1) PHE	(2) PHH	(3) Tax t_n^j	(4) t_n^j+ FEE	(5) t_n^j+ Productivity	(6) t_n^j+ Trade Costs	(7) t_n^j+ IO	(8) No IO
Robustness Model I: $\alpha_n^j \times 2$								
Panel A: Share of Dirty Sectors' Output								
Tax Rate	2.719***	0.166	-0.512**	-0.281**	-0.032	-0.085	-0.501**	-0.042
	(0.312)	(0.128)	(0.194)	(0.115)	(0.0312)	(0.177)	(0.203)	(0.191)
R-squared	0.745	0.048	0.323	0.193	0.014	0.011	0.268	0.002
Panel B: Emissions Composition Effects								
Tax Rate	5.154***	0.187	-2.460***	-1.566***	-0.036	-0.129	-2.471**	-0.823
	(1.470)	(0.498)	(0.852)	(0.498)	(0.0671)	(0.758)	(0.958)	(1.106)
R-squared	0.416	0.004	0.422	0.363	0.007	0.001	0.284	0.026
Robustness Model II: $\alpha_n^j \times 0.5$								
Panel A: Share of Dirty Sectors' Output								
Tax Rate	3.590***	0.566	-0.913*	-0.412	-0.180	-0.183	-1.041*	-0.226
	(0.572)	(0.485)	(0.476)	(0.325)	(0.136)	(0.753)	(0.519)	(0.720)
R-squared	0.790	0.038	0.137	0.035	0.027	0.003	0.129	0.005
Panel B: Emissions Composition Effects								
Tax Rate	5.423**	0.347	-5.704***	-3.881***	-0.290	-0.681	-6.084**	-3.443
	(1.989)	(1.911)	(1.868)	(1.170)	(0.239)	(2.905)	(2.232)	(4.203)
R-squared	0.329	0.001	0.399	0.333	0.028	0.002	0.276	0.031
Observations	33	33	33	33	33	33	33	33

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Robustness under different θ^j

	(1) PHE	(2) PHH	(3) Tax t_n^j	(4) t_n^j+ FEE	(5) t_n^j+ Productivity	(6) t_n^j+ Trade Costs	(7) t_n^j+ IO	(8) No IO
Robustness Model IV: $\theta = 4$ as in Simonovska and Waugh (2014)								
Panel A: Share of Dirty Sectors' Output								
Tax Rate	2.981***	0.053	-0.512**	-0.391**	-0.100	-0.220	-0.641**	-0.203
	(0.493)	(0.189)	(0.232)	(0.192)	(0.112)	(0.422)	(0.283)	(0.209)
R-squared	0.791	0.002	0.138	0.090	0.013	0.012	0.143	0.033
Panel B: Emissions Composition Effects								
Tax Rate	3.026**	0.0167	-3.289***	-2.603***	-0.172	-1.474	-2.984***	-0.981
	(1.237)	(0.439)	(0.852)	(0.753)	(0.495)	(1.173)	(1.077)	(0.819)
R-squared	0.305	0.000	0.308	0.253	0.003	0.056	0.225	0.054
Observations	33	33	33	33	33	33	33	33

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

values from Caliendo and Parro (2015). In this subsection, we set the values of θ^j at 4, which is the preferred estimate in Simonovska and Waugh (2014), to check the robustness of our findings. We repeat the exercises in section 4 and section 5 and report the regression results in Table 6. Our main findings that the PHE exists and the PHH is unsupported are robust over the values of θ. The PHH holds after we control all other comparative advantage forces and fails after we add the forces of productivity and trade costs into the model. Among the three forces in the model, productivity plays the most significant role in the failure of the PHH, followed by trade costs.

6.3 Factor endowment effect

It is well documented in the literature that as the pollution-intensive sectors tend to be capital-intensive, the effect of a country's relative capital and labor endowment will counteract the PHE. However, our finding in subsection 5.2 suggests the argument that the FEE dominates the PHE is not supported. Therefore, in this subsection, we recalibrate the factor intensity parameters and perform the counterfactual exercises in section 4.2, 5.1 and 5.2 to check the robustness of our findings on the relation between the PHE and the FEE.

Recall that the production function (5) obtains the following property:

$$\frac{\gamma_{k,n}^j}{\gamma_{l,n}^j} = \frac{r_n k_n^j}{w_n l_n^j} \tag{24}$$

According to equation (24), we calibrate $\gamma_{k,n}^j$ and $\gamma_{l,n}^j$ with data on the sectoral wage bill and return to capital in the benchmark case. If the wage rate and capital rent are equalized across countries, the capital-labor intensity of sector j relative to sector h equals the ratio of their γ parameters, i.e., $\frac{k_n^j/l_n^j}{k_n^h/l_n^h} = \frac{(r_n k_n^j)/(w_n l_n^j)}{(r_n k_n^h)/(w_n l_n^h)} = \frac{\gamma_{k,n}^j/\gamma_{l,n}^j}{\gamma_{k,n}^h/\gamma_{l,n}^h}$. In this case, calibrating $\gamma_{k,n}^j$ and $\gamma_{l,n}^j$ also directly pins down the capital-to-labor ratio in each sector. However, in reality, the wage rate and capital rent could be highly dispersed across sectors, and therefore the sectoral labor and capital intensity that we inferred from the compensation data might be inconsistent with the intensity calculated directly by factor input data. Since the FEH is completely about the capital-to-labor ratio, we address this concern by calibrating the model in an alternative way that directly uses capital-to-labor ratio. Notice that with the factor price equalization assumption, we rewrite equation (24) as

$$\frac{\gamma_{k,n}^j}{\gamma_{l,n}^j} = \frac{r_n k_n^j}{w_n l_n^j} = \frac{k_n^j/K_n}{l_n^j/L_n} \cdot \frac{r_n K_n}{w_n L_n}, \tag{25}$$

which suggests that we can calibrate the $\gamma_{k,n}^j$ and $\gamma_{l,n}^j$ with data on sectoral factor input and national labor income share in value added. We use the sectoral labor and capital stock data from the WIOD Social Economic Account (SEA) and calculate the national labor share from the INDSTAT2. We then impose the same counterfactual exercises as in section 4.2, 5.1 and 5.2 to examine the relative strength of PHE and the FEE. The results reported in Table (7) are consistent with our main findings in Table (2). In column (1), the insignificant relationships between environmental regulation stringency and the effects on both dirty sectors' output and emissions suggest that the PHH is still unsupported by our full-fledged model. After controlling for all other sources of comparative advantage, only the PHE works in the model and leads to the PHH pattern. Most importantly, column (3) suggests that even when the $\gamma_{k,n}^j$ and $\gamma_{l,n}^j$ fully reflect the information of factor intensity in the real data, the FEE does not cancel out the PHE.

To further shed light on the results on the FEE and the PHE, we go further to examine the premise of the FHH that pollution intensity is highly correlated with capital intensity at sector level. On a worldwide basis, the correlation between capital-to-labor ratio[17] and emissions intensity in the 13 manufacturing sectors is 0.64, which is comparable to that in the literature (e.g. Cole and Elliott (2003)). However, most of this relatively high correlation is caused by the *coke, refined petroleum and nuclear fuel* sector, which is both extremely capital- and pollution-intensive.[18] After excluding this sector, the correlation in the remaining 12 sectors declines to

[17]The ratio is reported in Table 8.

[18]It is reasonable to believe this sector is an outlier in the sample, as it is 3.6 times dirtier than the second most pollution-intensive sector and 1.5 times more capital intensive than the second most capital-intensive sector.

Table 7: Robustness of relative effects of the PHE and the FEE

	(1) PHH	(2) Tax t_n^j	(3) t_n^j+ FEE
Robustness Model V: Investigating the FEE with factor stock data			
Panel A: Share of Dirty Sectors' Output			
Tax Rate	0.305	-0.252**	-0.113*
	(0.232)	(0.103)	(0.0630)
R-squared	0.043	0.178	0.061
Panel B: Emissions Composition Effects			
Tax Rate	0.340	-0.909**	-0.454**
	(0.825)	(0.392)	(0.180)
R-squared	0.004	0.208	0.139
Observations	33	33	33

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

-0.16. When looking into the correlation in each country, we find vast heterogeneity. There are high correlations (higher than 0.9) in some developing countries, such as Brazil, Indonesia, and Russia. However, in a majority of countries, the correlation coefficients are very low: smaller than 0.5 in 20 countries and even below 0 in 4 countries. Thus, we believe that the premise that pollution-intensive sectors are capital intensive is not fully supported by our sample data and that the validity of the conventional prediction that the FEE offsets the PHE should be questioned.

7 Conclusion

The *pollution haven hypothesis* (PHH) and *Pollution Haven Effect* (PHE) are important economic research topics in the trade and environment literature. This paper quantifies their effects with a general equilibrium model including all manufacturing sectors and all major economies in the world. Our model takes into consideration multiple comparative advantage forces including factor endowment, productivity, trade costs, environmental regulation, and the input-output linkage in production, and therefore, we can obtain the comprehensive worldwide effects in the wake of exogenous environmental policies and trade liberalization shocks. The model is highly tractable, in that it enables us to decompose the emissions effects into scale, composition and technique effects to understand the underlying economics mechanism of changes in pollution.

We observe a robust PHE from a counterfactual exercise in which we equalize the sectoral emissions tax rate to a world average level. We find the direct technique effects from changes in the tax rate fully explain the pollution effects and that the scale and composition effects are economically small. Then, we impose a 20% worldwide reduction in trade costs to examine the PHH and quantify the net effect of globalization on the environment. We find no evidence for the hypothesis. The environmental regulation factor plays a minor role in affecting trade, indicated by the small composition effects in both counterfactual exercises. Moreover, we find a net increase in pollution induced by trade liberalization. The world economy grows and become more specialized in dirty sectors due to the reduced trade costs.

We then assess the PHH implied by the PHE by first eliminating all the comparative advantage forces in the model and then adding these forces back to the model one at a time. We find that the productivity and trade costs largely determine the evolution of international specialization and trade and, thus, cover the PHH. The factor endowment hypothesis is not so powerful as commonly thought. The input-output linkage intensifies the effects of PHH in a model with solely tax rate differences but does not make qualitative differences when abstracted from the model. Our findings are robust across different specifications of emissions elasticity and trade elasticity.

In conclusion, we develop a framework to understand the ambiguous PHH with a strong PHE from the quantitative perspective. We find that environmental regulations determine the pollution abatement activities, but their effects on underlying international specialization are small and dominated by other forces such as productivity and trade costs. However, except for the factor endowment hypothesis, there is no classical theory guiding us to predict the general pattern of interaction between productivity, geography and environment through international trade, which awaits exploration in future research.

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Appendix

A Data Description

We list the 33 economies in our sample by groups classified according to the emissions tax rates. The group of countries with a national emissions tax rate higher than 0.3% includes Austria, Canada, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, the United Kingdom, Hungary, Ireland, Italy, Japan, Korea, the Netherlands, Poland, Portugal, Slovak Republic, Sweden, Turkey, and the United States. The countries with a low national emissions tax rate are Australia, Bulgaria, Brazil, China, Indonesia, India, Lithuania, Mexico, Romania, Russia, and a constructed rest of world.

Trade and Production Data

We obtained the sectoral bilateral trade, gross output, and value added data from World Input Output Database. We use the 2013 released input-output table and follow their sector classification, which is based on ISIC revision 3. To concentrate on the conventional tradable sectors, we construct a dataset with 13 manufacturing sectors. To do this, we add intermediate input from agricultural and service sectors into value added and drop the gross output of these sectors from the national output. We then define the sectors as clean or dirty by their emissions intensity. We treat 7 of them as clean sectors, with the highest intensity being 3.21, and the remaining 6 as dirty, with the lowest intensity being 6.87; we set the cutoff for this relatively large difference. Table 8 lists all the sectors, their emissions intensity and, accordingly, the clean or dirty classification. To distinguish the wage bill and return to capital in the value added, we obtain the value-added and wage bill data from the UNIDO, calculate the share and combine it with the information from the WIOD.

The following data are mainly used in calibrating fundamentals. To work out the national wage rate and return to capital, we obtain the employment (measured by the number of people involved) and capital stock from Penn World Table 8.1. We adjust the labor endowment using the index of human capital per person in PWT. For the RoW data, we calculate the labor endowment in all the countries out of our sample and sum them together. The capital stock is measured in 2005 US dollars. We convert the data into 2007 US dollars using the Producer Price Index in International Financial Statistics (IFS) from the IMF. The original price data are based on 2010 US dollars. Thus, we first convert the data to 2010 US dollars by dividing the

2005 index, and then multiply by the 2007 index.

In the robustness analysis, we use the labor and capital stock in every sector in every country from the Social Economic Account (SEA) in the WIOD. Specifically, we use the total hours worked by persons engaged as labor input and the real fixed capital stock as capital input. The capital stock is measured by 1995 prices in national currency. As in equation (25), we only use the share of factor input and our model is static; there is no problem with the price level. However, we need to convert the measuring currency into 1995 US dollars. We use the 1995 annual average exchange rate from the IFS. The SEA reports data for 40 real economies in the WIOD, except for RoW. Again, as we only use the share instead of the value of factor input, we replace the RoW share with the aggregated share of the 8 economies that are not in our sample.

Environmental Data

We obtain the sectoral pollution data from the Environmental Accounts in the WIOD. The database reports the emissions of 8 types of air pollutants. We include the emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC) in our sample. The choice of pollutants aligns as much as possible with that of Shapiro and Walker (2018), for we adopt their estimation of the emissions elasticity in our calibration and empirical analysis.

To capture the cross-country differences in abatement efficiency, we obtain the environment-related tax revenue from the OECD Environment Database. The database reports tax revenue in US dollars for 83 countries, which enables us to construct the tax revenue for the RoW. However, as the data for most countries are estimated, instead of recorded, there are several abnormal values. Thus, we assume countries that are similar in GDP, the structure of industries, and geographic location are also similar in environmental regulation. We therefore replace the negative revenue of Mexico with the data from Argentina. The database does not include Indonesia and Russia, so we plug in the data for Malaysia and China as substitutes, respectively. In the above cases, we scale the tax revenue by GDP and replace the missing data with shares.

B Derivations

In this section, we derive the prices in equation (8) and the bilateral expenditure share in equation (10) from the distribution of efficiency, and the effect decomposition in equation (22).

Table 8: Sector List and Emissions Intensity

ID	Sector	ISIC Code	Trade Elasticity θ^j	K/L	Emissions Intensity e_n^j	Group
1	Food, Beverages and Tobacco	15-16	3.13	3.08	2.20	Clean
2	Textiles and Textile Products, Leather and Footwear	17-19	8.10	1.74	2.23	Clean
3	Wood and Products of Wood and Cork	20	11.50	0.77	3.21	Clean
4	Pulp, Paper, Paper , Printing and Publishing	21-22	11.50	4.04	2.43	Clean
5	Coke, Refined Petroleum and Nuclear Fuel	23	11.50	19.98	58.07	Dirty
6	Chemicals and Chemical Products	24	3.13	8.82	6.87	Dirty
7	Rubber and Plastics	25	3.13	3.18	13.37	Dirty
8	Other Non-Metallic Mineral	26	3.13	4.26	16.15	Dirty
9	Basic Metals and Fabricated Metal	27-28	5.22	8.83	11.38	Dirty
10	Machinery, Nec	29	3.13	3.48	0.67	Clean
11	Electrical and Optical Equipment	30-33	8.84	13.78	1.09	Clean
12	Transport Equipment	34-35	3.13	10.38	0.58	Clean
13	Manufacturing, Nec; Recycling	36-37	3.98	1.28	9.59	Dirty

B.1 Prices and Expenditure Shares

The efficiency of country i in producing an intermediate good ω^j in sector j is the realization of a random variable $A_i^{j(1-\alpha_i^j)}$ drawn from the distribution $F_i^j(A) = \exp\left(-\lambda_i^j A^{-\theta^j}\right)$. The distribution of the price of goods that country i can supply to country n is

$$G_{ni}^j(p) = Pr\left[p_{ni}^j < p\right] = Pr\left[A_i^{j(1-\alpha_i^j)} > \frac{\kappa_{ni}^j \psi_i^j}{p}\right] = 1 - \exp\left(-\lambda_i^j \left(\frac{\kappa_{ni}^j \psi_i^j}{p}\right)^{-\theta^j}\right). \tag{26}$$

The distribution of the price of goods that country n actually buys is

$$G_n^j(p) = Pr\left(P_n^j < p\right) = 1 - \prod_{i=1}^{N}\left[1 - G_{ni}^j(p)\right] = 1 - e^{-\Phi_n^j p^{\theta^j}}, \tag{27}$$

where $\Phi_n^j = \sum_{i=1}^N \lambda_i^j \left(\kappa_{ni}^j \psi_i^j\right)^{-\theta^j}$. According to the production function of aggregate sectoral goods, the price distribution is a CES aggregation of the price of all intermediate goods, which is

$$\begin{aligned}
\left(P_n^j\right)^{1-\sigma^j} &= \int_0^\infty p^{1-\sigma^j}\, dG_n^j(p) \\
&= \left(\Phi_n^j\right)^{-\frac{1-\sigma^j}{\theta^j}} \int_0^\infty \left(\Phi_n^j p^{\theta^j}\right)^{\frac{1-\sigma^j}{\theta^j}} e^{-\Phi_n^j p^{\theta^j}}\, d\left(\Phi_n^j p^{\theta^j}\right). \\
&= \left(\Phi_n^j\right)^{-\frac{1-\sigma^j}{\theta^j}} \left[\Gamma\left(\frac{\theta^j + 1 - \sigma^j}{\theta^j}\right)\right]
\end{aligned} \tag{28}$$

Then it is easy to obtain equation (8). To derive the expenditure share, note that π_{ni}^j is also the probability that country i provides a good to country n at the lowest price among all countries, and therefore,

$$
\begin{aligned}
\pi_{ni}^{j} &= Pr\left[\frac{\kappa_{ni}^{j}\psi_{i}^{j}}{A_{i}^{j(1-\alpha_{i}^{j})}} \leq \min_{d\neq i}\frac{\kappa_{nd}^{j}\psi_{d}^{j}}{A_{d}^{j(1-\alpha_{d}^{j})}}\right] \\
&= \prod_{d\neq i} Pr\left[\frac{\kappa_{ni}^{j}\psi_{i}^{j}}{A_{i}^{j(1-\alpha_{i}^{j})}} \leq \frac{\kappa_{nd}^{j}\psi_{d}^{j}}{A_{d}^{j(1-\alpha_{d}^{j})}}\right]
\end{aligned}. \tag{29}
$$

Using equation (26) and (27), we have

$$
\pi_{ni}^{j} = \frac{T_i\left(\kappa_{ni}^{j}\psi_{i}^{j}\right)^{-\theta^j}}{\Phi_n^j}\int_0^\infty \theta^j\,\Phi_n^j e^{-\Phi_n^j p^{\theta^j}}\,p^{\theta^j-1}\,dp.
$$

The integral is the probability density function with c.d.f $G_n^j(p)$ and, hence, equals 1; then, we obtain equation (10).

B.2 Emissions Effect Decomposition

To link the changes in pollution emissions to those in the tax rate and production, note that $z_n^j = \frac{\alpha^j}{t_n^j}p_n^j q_n^j$ and that the national emissions are the summation of all sectors:

$$
Z_n = \sum_{j=1}^{J}\sum_{i}\frac{\alpha^j}{t_n^j}X_{ni}^j = \sum_{j=1}^{J}\frac{\alpha^j}{t_n^j}\nu_n^j Y_n. \tag{30}
$$

The change in Z_n is then

$$
d\,Z_n = \sum_{j=1}^{J}\frac{\alpha^j}{t_n^j}\nu_n^j d\,Y_n + \sum_{j=1}^{J}\frac{\alpha^j}{t_n^j}Y_n d\,\nu_n^j - \sum_{j=1}^{J}\frac{\alpha^j}{t_n^j}\nu_n^j Y_n d\,ln t_n^j. \tag{31}
$$

Converting the changes in Y_n and ν_n^j into log-differences, then dividing by Z_n, we obtain the first row of equation (22). Adding equation (30) across country n and converting the changes in the same way, one can obtain the second decomposition equation.

C Solving the Model

The step-by-step solution process described in Caliendo and Parro (2015) is perfectly applicable to our model, except for one major difference. After solving $\pi_{in}^{j'}(\hat{\mathbf{w}})$ by conditions (16), (17), and (18) and given α^j, $\gamma_n^{j,h}$, $\gamma_{l,n}^j$, $\gamma_{k,n}^j$, s_n^j, we then need to solve for the counterfactual total expenditure $X_n^{j'}(\hat{\mathbf{w}})$ from the following condition:

$$
X_n^{j'} = \sum_{h=1}^{J}\left(1-\alpha_n^h\right)\gamma_n^{j,h}\sum_{i=1}^{N}\pi_{in}^{h'}X_i^{h'} + s_n^j\left(\hat{w}_n w_n L_n + \hat{r}_n\hat{K}_n r_n K_n + \sum_{j=1}^{J}\alpha_n^j\sum_{i=1}^{N}\pi_{in}^{j'}X_i^{j'} + D_n^{'}\right). \tag{32}
$$

Equation (32) is a system of $J \times N$ equations in $J \times N$ total expenditures, so we can rewrite the equations in matrix form:

$$\mathbf{\Omega}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)\mathbf{X} = \Delta\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$$

where $\mathbf{X}$ is the vector of expenditures in each sector and each country, and $\Delta\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ is a vector that contains the shares of each sector and each country in national value added and the trade deficit:

$$\mathbf{X} = \begin{pmatrix} X_1^{1'} \\ \vdots \\ X_1^{J'} \\ \vdots \\ X_n^{1'} \\ \vdots \\ X_n^{J'} \\ \vdots \\ X_N^{1'} \\ \vdots \\ X_N^{J'} \end{pmatrix}_{JN\times 1} ; \quad \Delta\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right) = \begin{pmatrix} s_1^1\left(\hat{w}_1 w_1 L_1 + \hat{r}_1 \hat{K}_1 r_1 K_1 + D_1^{'}\right) \\ \vdots \\ s_1^J\left(\hat{w}_1 w_1 L_1 + \hat{r}_1 \hat{K}_1 r_1 K_1 + D_1^{'}\right) \\ \vdots \\ s_n^1\left(\hat{w}_n w_n L_n + \hat{r}_n \hat{K}_n r_n K_n + D_n^{'}\right) \\ \vdots \\ s_n^J\left(\hat{w}_n w_n L_n + \hat{r}_n \hat{K}_n r_n K_n + D_n^{'}\right) \\ \vdots \\ s_N^1\left(\hat{w}_N w_N L_N + \hat{r}_N \hat{K}_N r_N K_N + D_N^{'}\right) \\ \vdots \\ s_N^J\left(\hat{w}_N w_N L_N + \hat{r}_N \hat{K}_N r_N K_N + D_N^{'}\right) \end{pmatrix}_{JN\times 1}.$$

The $\mathbf{\Omega}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ is constructed by adding three square matrices I, $\mathbb{H}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$, and $\mathbb{T}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$. The matrix I is the identity matrix with dimension $JN \times JN$. The matrix $\mathbb{H}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ is formally defined as

$$\mathbb{H}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right) = \begin{pmatrix}
\left(1-\alpha_1^1\right)\gamma_1^{1,1}\pi_{1,1}^1 & \dots & \left(1-\alpha_1^J\right)\gamma_1^{1,J}\pi_{1,1}^J & \dots & \left(1-\alpha_1^1\right)\gamma_1^{1,1}\pi_{N,1}^1 & \dots & \left(1-\alpha_1^J\right)\gamma_1^{1,J}\pi_{N,1}^J \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\left(1-\alpha_1^1\right)\gamma_1^{J,1}\pi_{1,1}^1 & \dots & \left(1-\alpha_1^J\right)\gamma_1^{J,J}\pi_{1,1}^J & \dots & \left(1-\alpha_1^1\right)\gamma_1^{J,1}\pi_{N,1}^1 & \dots & \left(1-\alpha_1^J\right)\gamma_1^{J,J}\pi_{N,1}^J \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\left(1-\alpha_n^1\right)\gamma_n^{1,1}\pi_{1,n}^1 & \dots & \left(1-\alpha_n^J\right)\gamma_n^{1,J}\pi_{1,n}^J & \dots & \left(1-\alpha_n^1\right)\gamma_n^{1,1}\pi_{N,n}^1 & \dots & \left(1-\alpha_n^J\right)\gamma_n^{1,J}\pi_{N,n}^J \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\left(1-\alpha_n^1\right)\gamma_n^{J,1}\pi_{1,n}^1 & \dots & \left(1-\alpha_n^J\right)\gamma_n^{J,J}\pi_{1,n}^J & \dots & \left(1-\alpha_n^1\right)\gamma_n^{J,1}\pi_{N,n}^1 & \dots & \left(1-\alpha_n^J\right)\gamma_n^{J,J}\pi_{N,n}^J \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\left(1-\alpha_N^1\right)\gamma_N^{1,1}\pi_{1,N}^1 & \dots & \left(1-\alpha_N^J\right)\gamma_N^{1,J}\pi_{1,N}^J & \dots & \left(1-\alpha_N^1\right)\gamma_N^{1,1}\pi_{N,N}^1 & \dots & \left(1-\alpha_N^J\right)\gamma_N^{1,J}\pi_{N,N}^J \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\left(1-\alpha_N^1\right)\gamma_N^{J,1}\pi_{1,N}^1 & \dots & \left(1-\alpha_N^J\right)\gamma_N^{J,J}\pi_{1,N}^J & \dots & \left(1-\alpha_N^1\right)\gamma_N^{J,1}\pi_{N,N}^1 & \dots & \left(1-\alpha_N^J\right)\gamma_N^{J,J}\pi_{N,N}^J
\end{pmatrix}_{JN\times JN}.$$

Moreover, we define the matrix $\mathbb{T}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ as

$$\mathbb{T}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right) = \begin{pmatrix} s_1^1\alpha_1^1\pi_{1,1}^1 & \cdots & s_1^1\alpha_1^J\pi_{1,1}^J & \cdots & s_1^1\alpha_1^1\pi_{N,1}^1 & \cdots & s_1^1\alpha_1^J\pi_{N,1}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_1^J\alpha_1^1\pi_{1,1}^1 & \cdots & s_1^J\alpha_1^J\pi_{1,1}^J & \cdots & s_1^J\alpha_1^1\pi_{N,1}^1 & \cdots & s_1^J\alpha_1^J\pi_{N,1}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_n^1\alpha_n^1\pi_{1,n}^1 & \cdots & s_n^1\alpha_n^J\pi_{1,n}^J & \cdots & s_n^1\alpha_n^1\pi_{N,n}^1 & \cdots & s_n^1\alpha_n^J\pi_{N,n}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_n^J\alpha_n^1\pi_{1,n}^1 & \cdots & s_n^J\alpha_n^J\pi_{1,n}^J & \cdots & s_n^J\alpha_n^1\pi_{N,n}^1 & \cdots & s_n^J\alpha_n^J\pi_{N,n}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_N^1\alpha_N^1\pi_{1,N}^1 & \cdots & s_N^1\alpha_N^J\pi_{1,N}^J & \cdots & s_N^1\alpha_N^1\pi_{N,N}^1 & \cdots & s_N^1\alpha_N^J\pi_{N,N}^J \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_N^J\alpha_N^1\pi_{1,N}^1 & \cdots & s_N^J\alpha_N^J\pi_{1,N}^J & \cdots & s_N^J\alpha_N^1\pi_{N,N}^1 & \cdots & s_N^J\alpha_N^J\pi_{N,N}^J \end{pmatrix}_{JN\times JN}$$

Finally, the $\boldsymbol{\Omega}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ matrix is defined as $\boldsymbol{\Omega}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right) = I - \mathbb{H}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right) - \mathbb{T}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$. Then, we take the invert of $\boldsymbol{\Omega}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ and solve the expenditures as

$$\mathbf{X} = \boldsymbol{\Omega}^{\mathbf{-1}}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)\Delta\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right).$$

With $\pi_{in}^{j'}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$ and $X_n^{j'}\left(\hat{\mathbf{w}}, \hat{\mathbf{r}}\right)$, we obtain the proportional difference between the simulated data and real data, then adjust our next guess of $\hat{\mathbf{w}}$ and $\hat{\mathbf{r}}$ accordingly, and proceed.