International Differences in Emissions Efficiency and the Drivers of Emissions Embodied in Trade

Pablo R. Liboreiro

1 Introduction

The environmental consequences of international trade have been the subject of academic debate for more than three decades. Indeed, the first rigorous contributions to the issue date back to the late 1970s [14, 15]. However, it was not until the 1990s that the debate entered the realm of economic accounting and econometrics [5], as increasingly detailed datasets became available and the computational capabilities of personal computers improved substantially.

This is particularly true in the case of input-output accounting with environmental satellite accounts, which makes it possible to measure, among other things, national carbon footprints [7, 11] and the emissions content of international trade [8]. Today, it appears evident that the emissions content of international trade exhibits a pronounced North–South structure: in general, advanced economies are net importers of pollutants — insofar as the pollutants embodied in the goods they consume exceed those embodied in the goods they produce — whereas developing economies are net exporters.

Additional analyses of this North–South structure have sometimes led researchers to identify the existence of "pollution havens" in developing countries on the basis of input-output data [3, 9, 13] or other sources of information [1, 12]. Indeed, since environmental quality is generally assumed to be a normal good whose demand increases with income [4], environmental standards are expected to be weaker in countries with lower per capita income. Regulatory differences therefore become a driver of international trade, as pollution-intensive industries tend to locate in countries with less stringent environmental regulations, namely developing economies, which thereby become potential pollution havens.

Nevertheless, the North–South structure of emissions embodied in trade is not necessarily evidence of the existence of pollution havens in the South. As emphasised since Grossman and Krueger [10], the emissions content of trade may arise either from differences in the composition of output across countries (the *composition effect*) or from differences in production techniques (the *technique effect*).

Consider, for example, the ship-breaking industry in Alang, India, where ships are deliberately beached and dismantled manually using blowtorches. This activity is often portrayed as a paradigmatic pollution haven. At first glance, ship-breaking appears to locate in India precisely because environmental standards are weaker, so that international trade induces a shift in output composition toward more pollution-intensive activities. As a result, the exports generated by this industry embody a large amount of pollution, making India a net exporter of pollutants.

However, it could also be the case that ship-breaking is located in India because it is a labour-intensive activity and that it is particularly pollution-intensive there because of the production techniques employed. If pollution is conceived as a joint product [5], productive resources such as capital and labour may be allocated either to the dismantling activity itself or to pollution-abatement activities. When resource efficiency is low, as in India, efforts devoted to pollution mitigation yield relatively limited results. Furthermore, weaker environmental standards — and therefore a lower relative cost of pollution compared with other production factors — reduce the incentive to allocate resources to abatement activities. Consequently, all economic activities in India, not only ship-breaking, become more pollution-intensive, making the country a net exporter of pollutants insofar as its exports embody more pollution than its imports.

Many recent studies analysing input-output accounts have overlooked the distinction between composition and technique effects [3, 13]. Nevertheless, some studies do take this distinction into account.

Douglas and Nishioka [8], working within a Heckscher–Ohlin framework, propose a representation of production techniques in which emissions-output coefficients are decomposed into an industry-specific component and a country-specific component reflecting efficiency levels. The former allows estimation of the emissions content of trade attributable to the composition effect, whereas the latter captures the technique effect. Their statistical analysis leads them to conclude that there is no evidence supporting the pollution haven hypothesis, since emissions embodied in trade appear to be driven not by differences in output composition but by international differences in emissions efficiency.

The approach proposed by Douglas and Nishioka [8], however, presents several limitations. The principal limitation is that, since emissions are treated as a joint product, it is not immediately clear why emissions themselves should exhibit productivity differences across countries. Nor is the role of environmental standards and, therefore, the cost of polluting explicitly incorporated into their framework, as pollution mitigation through the use of productive resources is not modelled directly.

Other methods proposed in the literature appear to suffer from even greater shortcomings. For example, in order to distinguish between composition and technique effects, Duan et al. [9] use U.S. emissions-output coefficients as a benchmark. Any deviation from this benchmark in the emissions content of trade is then interpreted as a composition effect. This is clearly a cruder procedure than that of Douglas and Nishioka [8], as it ignores cross-country differences in efficiency as well as intra-industry differences in emissions intensity arising from product heterogeneity. Moreover, the procedure lacks a clear theoretical foundation.

The present paper proposes a framework based on Copeland and Taylor [4, 5], in which emissions enter the production function because they are a joint product that can be mitigated. Productive resources — capital and labour — may therefore be allocated either to productive activities themselves or to pollution-abatement activities, generating an apparent substitution between emissions and conventional production factors. Furthermore, the efficiency of this emissions-resource trade-off varies across countries.

Using cross-sectional regressions, and after estimating capital and labour in internationally comparable efficiency units, emissions-output coefficients are decomposed into four components. Three of these are country-specific and capture how production techniques vary across countries according to general efficiency levels, capital abundance, and emissions abundance per efficiency unit. The remaining component is industry-specific and represents the intrinsic emissions intensity of production once the previous factors have been isolated.

This decomposition of emissions-output coefficients is then used to measure the contribution of each component to the emissions content of international trade through a structural decomposition analysis comparing the observed economy with a counterfactual benchmark in which all industries in all countries share identical emissions intensities. In this hypothetical benchmark, the net emissions content of trade is zero whenever countries' trade balances are in equilibrium. Consequently, the emissions content of trade can be interpreted as arising from four drivers: international differences in efficiency levels, capital abundance, emissions abundance per efficiency unit, and output composition.

The empirical analysis uses data from the World Input-Output Database (WIOD), Release 2016, covering 43 countries plus a composite Rest-of-the-World economy and 56 industries over the period 2000–2014. These data are combined with industry- and country-level carbon dioxide emissions data compiled by the Joint Research Centre of the European Commission, which are fully consistent with the WIOD accounts.

The results reveal that the emissions-output ratio decreases with the capital-labour ratio measured in efficiency units and increases with emissions per efficiency unit, with both effects being statistically significant. Nevertheless, the principal driver of differences in emissions-output ratios — and therefore of emissions embodied in trade — is cross-country variation in efficiency levels. This result is consistent with Douglas and Nishioka [8]. However, regarding the observed increase in emissions embodied in trade over time, international differences in emissions per efficiency unit appear to have played the dominant role.

Output composition, by contrast, plays a smaller role, although the evidence does not allow rejection of the hypothesis that a positive association exists between countries' emissions abundance and the output-composition component of emissions embodied in trade. More specifically, the statistical tests reject the existence of a strong linear relationship between the two variables, but they also reject the possibility that the observed association is purely random.

These findings have important policy implications. In particular, they suggest that, contrary to the conclusions of Douglas and Nishioka [8], there may indeed be scope for public policy to influence the emissions content of trade. On the one hand, pollution taxes may affect the emissions intensity of output without necessarily altering output composition, insofar as greater amounts of capital and labour are allocated to pollution-abatement activities. On the other hand, such policies may also influence output composition itself, since the empirical results do not allow this possibility to be ruled out. Finally, an increase in the capital-labour ratio — for example, resulting from a higher savings rate — may also contribute to reducing emissions intensity.

The remainder of the paper is organised as follows. Section 2 develops the theoretical framework and derives the decomposition of emissions-output coefficients and the corresponding structural decomposition of the emissions content of trade. Section 3 describes the data sources and the procedures used to reconcile the theoretical framework with the World Input-Output Database. Section 4 presents the estimation of the technological parameters and discusses the empirical properties of the estimated production techniques. Section 5 analyses the drivers of emissions embodied in international trade and evaluates the empirical relevance of the pollution haven hypothesis. Finally, Section 6 concludes and discusses the main policy implications of the results.

2 Production Techniques and Emissions Requirements

Consider a production function of the form

$$Y = \alpha F(E, \pi_K K, \pi_L L) \tag{1}$$

where Y denotes output, E emissions, K capital, L labour, and α, π_K, and π_L are technological parameters. The parameters π_K and π_L represent the capital-augmenting and labour-augmenting components of technology, respectively, such that $\tilde{K} = \pi_K K$ and $\tilde{L} = \pi_L L$ denote capital and labour measured in efficiency units. In turn, α is a Hicks-neutral productivity parameter capturing both total factor productivity and the productivity of pollution abatement activities.

The reason emissions enter the production function despite being a joint product is that there exists an abatement technology $A[\alpha, E(Y), \tilde{K}, \tilde{L}]$ through which capital and labour may be allocated to pollution mitigation. As a consequence, emissions appear in the production function as if they were an additional factor substitutable with capital and labour (see [4] for a formal derivation). Nevertheless, despite this apparent symmetry, emissions are not a production factor, and therefore there are no theoretical grounds to expect the existence of "emissions-augmenting" technologies in (1).

Starting from (1) and following a line of reasoning analogous to Davis and Weinstein [6], it is possible to represent emissions-output coefficients for industries $i = 1, 2, \ldots, N$ and countries $c = 1, 2, \ldots, C$ in a way that allows statistical estimation of the relevant parameters. Let a^c_{fi} denote the factor-output coefficient of sector i in country c for factor

$f \in \{E, K, L\}$. Then:

$$\ln(a^c_{fi}) = -\ln(\alpha^c) + \ln(\bar{a}_{fi}) + \gamma_f \ln\left(\frac{\tilde{K}^c}{\tilde{L}^c}\right) + \delta_f \ln\left(\frac{E^c}{\tilde{L}^c}\right) + \varepsilon^c_{fi} \tag{2}$$

where α^c is a country-specific global productivity parameter, $\bar{a}_{fi}$ denotes the factor-output coefficient (measured in efficiency units) for factor f in sector i common across countries, γ_f measures the effect of capital abundance on factor intensity, δ_f captures the effect of emissions abundance on factor intensity, and ε^c_{fi} is an error term.

For α^c to be interpreted as a global productivity parameter, the coefficients γ_f and δ_f must satisfy the following normalisation conditions:

$$\sum_{f \in \{E,K,L\}} \gamma_f = 0 \tag{3}$$

$$\sum_{f \in \{E,K,L\}} \delta_f = 0 \tag{4}$$

In addition, solving (2) requires an extra normalisation condition. A common approach is to measure productivity relative to a benchmark country in the sample:

$$\alpha^1 = 1 \tag{5}$$

Equation (2) has several advantages. First, it is relatively straightforward to estimate using panel-data techniques with fixed effects. Second, it captures several phenomena that may arise in a production environment such as (1).

An increase in global productivity reduces the quantity of production factors required and decreases emissions per unit of output because abatement technology becomes more efficient.

Similarly, if capital becomes more abundant (that is, if the capital-labour ratio measured in efficiency units rises), this may induce changes in both factor-output coefficients and emissions-output coefficients through substitution effects. This would occur if pollution abatement technology were particularly capital-intensive or labour-intensive. In the former case, an increase in capital abundance would induce greater pollution abatement; in the latter case, it would reduce it.

Finally, the emissions-effective labour ratio constitutes a measure of emissions abundance and is likely the parameter capturing policy decisions. In particular, if pollution taxes τ differ across countries, one would expect the ratio between these taxes and efficiency wages to be inversely related to emissions per efficiency unit in each country:

$$\frac{\tau^c}{\tilde{w}^c} \propto \frac{\tilde{L}^c}{E^c}$$

An increase in pollution taxes would therefore induce a greater allocation of labour toward pollution abatement activities and consequently reduce emissions per efficiency unit. According to the theory underlying (1), this would occur through a decline in emissions-output coefficients across industries as firms allocate more resources to pollution mitigation.

The representation in (2) of emissions-output or factor-output coefficients has an additional advantage: it naturally provides a benchmark against which the importance of different drivers of the factor or emissions content of trade can be estimated. Consider the conventional expression in Trefler and Zhu [19]:

$$\mathbf{f}_f^\top = \mathbf{a}_f^\top \mathbf{T} = \mathbf{a}_f^\top (\mathbf{Y} - \mathbf{C}) \tag{6}$$

where $\mathbf{f}_f$ is a C-dimensional vector representing the net factor or emissions content of trade for each of the C countries in the sample, $\mathbf{a}_f$ is a CN-dimensional vector of emissions or factor coefficients per unit of net output in each of the N industries and C countries, $\mathbf{Y}$ is a $CN \times C$ quasi-diagonal matrix whose columns represent net output for each country, and $\mathbf{C}$ is a $CN \times C$ matrix whose columns represent final demand in each country.

Now define a vector $\bar{\mathbf{a}}_f$ such that:

$$\bar{\mathbf{a}}_f = \mathbb{E}(\bar{a}_{fi}) \left(\frac{\tilde{K}^w}{\tilde{L}^w} \right)^{\gamma_f} \left(\frac{E^w}{\tilde{L}^w} \right)^{\delta_f} \mathbf{i} \tag{7}$$

where $\mathbb{E}(\bar{a}_{fi})$ denotes the expectation of $\bar{a}_{fi}$:

$$\mathbb{E}(\bar{a}_{fi}) = \frac{\sum_{i=1}^{N} a_{fi} Y_i}{\sum_{i=1}^{N} Y_i}$$

$\mathbf{i}$ is a CN-dimensional vector of ones, $\tilde{K}^w/\tilde{L}^w$ is the world capital-labour ratio, and $E^w/\tilde{L}^w$ is the world emissions-labour ratio when labour and capital are measured in efficiency units. Thus, $\bar{\mathbf{a}}_f$ represents a hypothetical benchmark in which all industries in all countries exhibit identical factor or emissions intensities.

By construction, if countries' trade balances are zero ($\mathbf{i}^\top \mathbf{T} = \mathbf{0}_C^\top$, where $\mathbf{0}_C$ is a C-dimensional vector of zeros), then:

$$\bar{\mathbf{a}}_f^\top \mathbf{T} = \mathbf{0}_C^\top \tag{8}$$

Therefore:

$$\mathbf{f}_f^\top = (\mathbf{a}_f^\top - \bar{\mathbf{a}}_f^\top)\mathbf{T} \tag{9}$$

Equation (9) is particularly useful because, by construction, it represents the factor or emissions content of trade as the outcome of cross-country differences in efficiency levels, sectoral factor intensities, and capital and emissions abundance. Moreover, it provides the basis for quantifying the contribution of each of these components. To see this more clearly, it is useful to expand (9) using (2) and (7):

$$\begin{aligned} f_f^c &= \sum_{i=1}^{N} \left[\frac{\bar{a}_{fi}}{\alpha^c} \left(\frac{\tilde{K}^c}{\tilde{L}^c} \right)^{\gamma_f} \left(\frac{E^c}{\tilde{L}^c} \right)^{\delta_f} \exp(\varepsilon_{fi}^c) \right. \\ &\qquad \left. - \mathbb{E}(\bar{a}_{fi}) \left(\frac{\tilde{K}^w}{\tilde{L}^w} \right)^{\gamma_f} \left(\frac{E^w}{\tilde{L}^w} \right)^{\delta_f} \right] T_i^c \\ &= \sum_{i=1}^{N} \left(a_{fi}(Z) - a_{fi}(\bar{Z}) \right) T_i^c \end{aligned} \tag{10}$$

where

$$Z = (\alpha^c, \bar{a}_{fi}, \tilde{K}^c/\tilde{L}^c, E^c/\tilde{L}^c, \varepsilon_{fi}^c)$$

describes the observed state, while

$$\bar{Z} = (1, \mathbb{E}(\bar{a}_{fi}), \tilde{K}^w/\tilde{L}^w, E^w/\tilde{L}^w, 0)$$

denotes the benchmark state.

Applying the Shapley decomposition, the factor or emissions content of trade can then be expressed as the sum of five components:

$$f_f^c = \phi_\alpha^c + \phi_A^c + \phi_{K/L}^c + \phi_{E/L}^c + \phi_\varepsilon^c \tag{11}$$

where the Shapley contribution of factor m is:

$$\phi_m^c = \sum_{S \subseteq M \setminus \{m\}} \frac{|S|!(|M| - |S| - 1)!}{|M|!} \sum_{i=1}^{N} \left[a_{fi}(Z_S, \bar{Z}_{(-S-m)}, z_m) - a_{fi}(Z_S, \bar{Z}_{(-S-m)}, \bar{z}_m) \right] T_i^c$$

where

$$M = \{\alpha, A, K/L, E/L, \varepsilon\}$$

and Z_S denotes the subset of elements in vector Z indexed by S.

The decomposition in (10) therefore makes it possible to quantify the share of the factor or emissions content of trade attributable to each of the four drivers discussed above, together with an error component capturing measurement noise and variation arising from product heterogeneity within industries.

3 Data Issues

The methodology described above was applied to data from the World Input-Output Database (WIOD), Release 2016 [16, 17]. This database is, to date, one of the most comprehensive in terms of the number of industries, countries, and factors covered. WIOD

Release 2016, together with its underlying datasets, covers 56 sectors (classified according to ISIC Rev. 4) and 43 countries, plus a composite economy representing the rest of the world, for the period 2000–2014. The underlying data, included within the *Socio-Economic Accounts*, provide information on labour use (measured in thousands of persons engaged) and capital use (measured in current USD). In addition, the Joint Research Centre of the European Commission has published data on carbon dioxide emissions (measured in tonnes) by industry and country for the period 2000–2016, fully consistent with WIOD Release 2016.

Several issues arise with these data, many of which are common to similar international databases.

First, monetary variables such as capital stocks and value added are expressed at current prices, implying that they may fluctuate substantially from year to year because of exchange-rate movements. To address this issue, sectoral capital-stock and value-added data were converted into international dollars using purchasing-power-parity-adjusted exchange rates provided by the World Bank.

A second issue is that the database provides information on sectoral emissions for the composite economy representing the rest of the world, but does not provide corresponding information on capital and labour use. In order to bridge this gap, the following procedure was adopted. First, the ratios of labour and capital in the rest of the world relative to the aggregate of the 43 countries in the sample were obtained from Penn World Table version 10.0. PPP-adjusted exchange rates were then constructed using World Bank data in order to estimate the total quantities of labour and capital corresponding to the rest of the world. Subsequently, sectoral labour and capital coefficients per unit of value added were estimated using expected values from a group of countries whose GDP per worker differed by no more than 5% from that of the rest of the world. These countries were Bulgaria, Brazil, China, Indonesia, India, Romania, and Russia.

Another issue arising when attempting to reconcile world input-output tables with theoretical trade models is that the latter generally do not incorporate intermediate goods explicitly [19]. In practice, however, the factor or emissions content of trade in equation (6) is computed using world input-output tables as:

$$\mathbf{f}_f^\top = \mathbf{b}_f^\top (\mathbf{I} - \mathbf{A})^{-1} \left[(\mathbf{I} - \mathbf{A})\mathbf{X} - \mathbf{C} \right] \tag{12}$$

where $\mathbf{b}_f$ is a CN-dimensional vector of coefficients representing the amount of emissions or factors per unit of gross output, $\mathbf{A}$ is the global $CN \times CN$ input-output matrix, and $\mathbf{X}$ is a quasi-diagonal $CN \times C$ matrix whose columns represent gross output for each industry in each of the C countries.

The standard way of reconciling equations (6) and (12) is to assume:

$$\mathbf{a}_f^\top = \mathbf{b}_f^\top (\mathbf{I} - \mathbf{A})^{-1} \tag{13}$$

$$\mathbf{Y} = (\mathbf{I} - \mathbf{A})\mathbf{X} \tag{14}$$

and this is the approach adopted here.

Finally, another difficulty arising when matching theory and data is that theoretical models typically abstract from intertemporal trade between countries. In reality, however, countries may exhibit substantial current-account imbalances, implying that part of the factor or emissions content of trade is necessarily driven by these imbalances. In order to isolate this component, the approach proposed by Bowen, Leamer, and Sveikauskas [2] was followed, correcting countries' demand by their trade balances. Accordingly, the factor or emissions content of trade was computed as:

$$\mathbf{f}_f^\top = \mathbf{b}_f^\top (\mathbf{I} - \mathbf{A})^{-1} \left[(\mathbf{I} - \mathbf{A})\mathbf{X} - \mathbf{C} - \mathbf{c}_w \mathbf{b}^\top \right] \tag{15}$$

where $\mathbf{c}_w$ is a CN-dimensional vector representing world final demand ($\mathbf{c}_w = \mathbf{Ci}$), and $\mathbf{b}$ is a C-dimensional vector representing the ratio between each country's trade balance and world GDP.

4 Estimating Technology

After addressing the issues inherent in the database, the next step consisted of estimating the emissions-output coefficients for each industry and country according to equation (2). Although the present analysis is primarily concerned with emissions-output coefficients, it is necessary to estimate capital-output and labour-output coefficients simultaneously in order to recover the underlying technological parameters correctly. Moreover, according to equation (1), labour and capital must be expressed in efficiency units so that the parameter α genuinely captures differences in global productivity.

This can be done in several ways. In the present study, however, a method based on Trefler [18] was adopted. Under the assumptions that factor-productivity differences exist across countries, preferences are identical and homothetic internationally, markets are undistorted, and all countries employ identical technologies, the following condition holds:

$$\boldsymbol{\pi}_f = (\hat{\mathbf{v}}_f - \hat{\mathbf{s}}\mathbf{i}\mathbf{v}_f^\top)^{-1} \mathbf{f}_f^* \tag{16}$$

where $\mathbf{v}_f$ is a C-dimensional vector whose elements represent the total endowment of factor f available in country c, $\mathbf{s}$ is a C-dimensional vector containing each country's share in world output, and $\mathbf{f}_f^*$ is a C-dimensional vector representing the factor content of exports for each country under the assumption of identical technologies:

$$\mathbf{f}_f^{*\top} = \mathbf{a}_f^{*\top} \mathbf{T} \tag{17}$$

The vector $\mathbf{a}_f^*$ is not, however, the vector of coefficients directly observed in the data. Consequently, solving equation (16) requires assuming that all countries use identical technologies, but that each observed technology is drawn from a random distribution centred around a common technological benchmark [6]. Under this assumption, $\mathbf{a}_f^*$ may be estimated from the following regression:

$$\ln(a_{fi}^c) = \ln(a_{fi}^*) + \varepsilon_{fi}^c \tag{18}$$

Furthermore, because system (16) is overidentified, an additional normalisation condition is required. In the present case, the following assumption was imposed:

$$\pi_f^{USA} = 1 \tag{19}$$

Applying this procedure to both capital and labour ($f \in \{K, L\}$) yields the productivity parameters π_K and π_L, from which it becomes possible to compute the capital-labour ratio in efficiency units as well as emissions per efficiency unit.

Figures 1 and 2 display these ratios for the countries in the sample as a function of GDP per worker. As can be observed, once capital is measured in efficiency units, capital per worker is no longer correlated with GDP per worker. By contrast, emissions per efficiency unit remain strongly correlated with GDP per worker. Specifically, higher levels of GDP per worker are associated with lower emissions per efficiency unit. Moreover, the Pearson correlation coefficient for the latter relationship is substantially larger in absolute value than for the former.

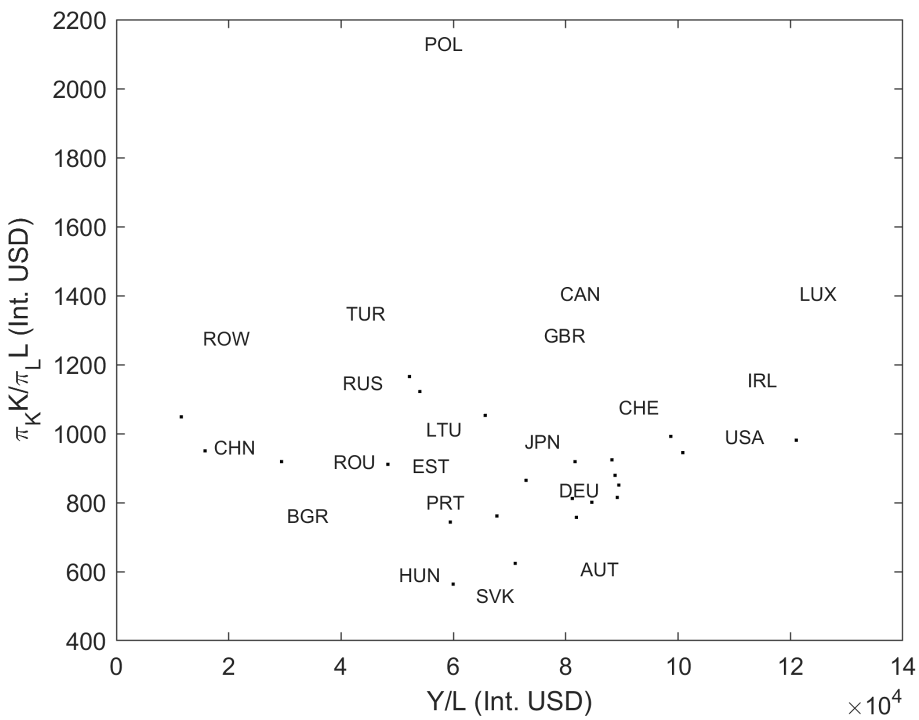

Figure 1: Capital per effective worker as a function of GDP per worker

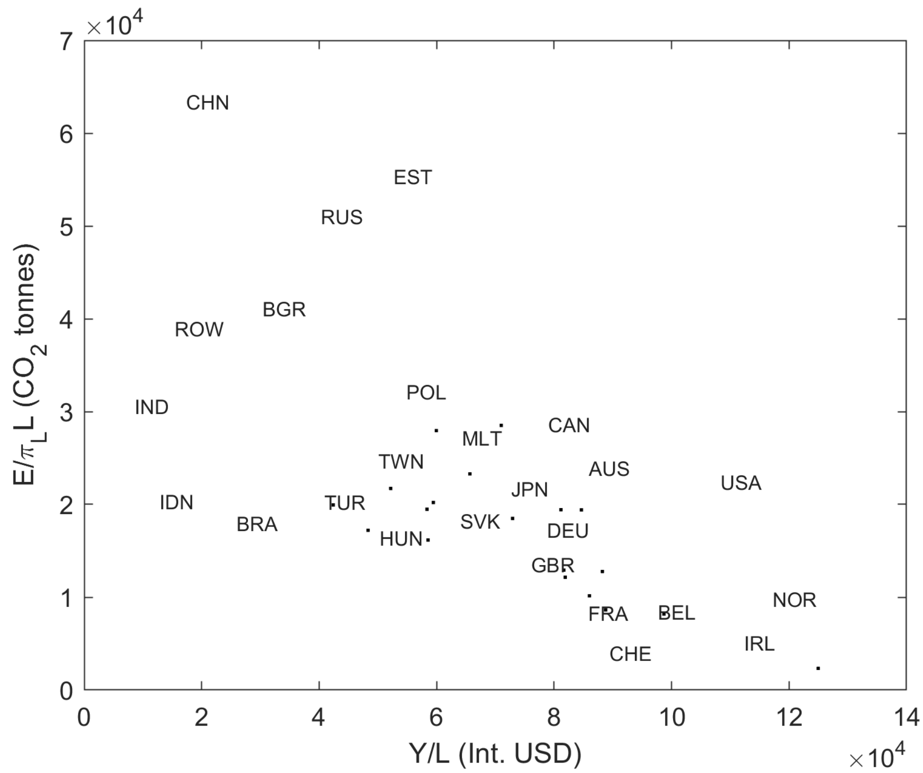

Figure 2: Emissions per efficiency unit as a function of GDP per worker

Once both effective capital and effective labour had been calculated, equation (2) was estimated. In order to assess the adequacy of the specification, the estimation proceeded sequentially by introducing one additional component at each stage. The following equations were therefore estimated:

$$\ln(a^c_{fi}) = \ln(\bar{a}_{fi}) + \varepsilon^c_{fi} \tag{20}$$

$$\ln(a^c_{fi}) = -\ln(\alpha^c) + \ln(\bar{a}_{fi}) + \varepsilon^c_{fi} \tag{21}$$

$$\ln(a^c_{fi}) = -\ln(\alpha^c) + \ln(\bar{a}_{fi}) + \delta_f \ln\left(\frac{E^c}{\tilde{L}^c}\right) + \varepsilon^c_{fi} \tag{22}$$

$$\ln(a^c_{fi}) = -\ln(\alpha^c) + \ln(\bar{a}_{fi}) + \gamma_f \ln\left(\frac{\tilde{K}^c}{\tilde{L}^c}\right) + \delta_f \ln\left(\frac{E^c}{\tilde{L}^c}\right) + \varepsilon^c_{fi} \tag{23}$$

In all cases, the normalisation conditions 3, 4 and $\alpha^{USA} = 1$ were imposed.

Table 1 reports the estimation results. As can be seen, both the Schwarz information criterion and the Akaike information criterion favour model (23), which is also the specification most consistent with the underlying theory.

Interestingly, the estimated coefficients are theoretically coherent. According to the signs of the γ parameters, an increase in capital abundance induces greater capital use and lower labour use per unit of output, while emissions intensity declines. Similarly, an increase in emissions per efficiency unit reduces both capital and labour use, which is consistent with the assumption that part of productive resources is allocated to pollution abatement activities. In other words, greater pollution allows firms to economise on capital and labour because fewer resources are required for mitigation activities. Moreover, all estimated parameters are statistically significant at the 99% confidence level.

With regard to the efficiency parameters α^c (not reported here), the null hypothesis $\alpha^c = 1$ could not be rejected at the 95% confidence level for several countries. This was the case for Australia, Spain, Greece, Japan, Lithuania, Mexico, the Netherlands, Slovakia, and Slovenia. Consequently, the normalisation condition was expanded to include these countries as well.

Table 1: Tests of Technological Variation

Model	(20)	(21)	(22)	(23)
γ_L	–	–	–	-0.31
				(0.02)
γ_K	–	–	–	0.44
				(0.03)
γ_E	–	–	–	-0.12
				(0.03)
δ_L	–	–	-0.18	-0.18
			(0.01)	(0.01)
δ_K	–	–	-0.17	-0.17
			(0.01)	(0.01)
δ_E	–	–	0.36	0.36
			(0.01)	(0.01)
Number of parameters	209	208	211	214
BIC	12543	10203	9119	8812
AIC	11103	8770	7672	7352

5 Drivers of Emissions Embodied in Trade

When the emissions content of trade is computed according to equation (15) using data from the World Input-Output Database, the pattern represented in Figure 3 emerges. Among net exporters of emissions, China, Russia, and the composite economy representing the rest of the world stand out prominently. Together, these three economies account for more than 80% of global net emissions exports. On the import side, the largest net importers of emissions are the United States, Germany, the United Kingdom, France, and Japan.

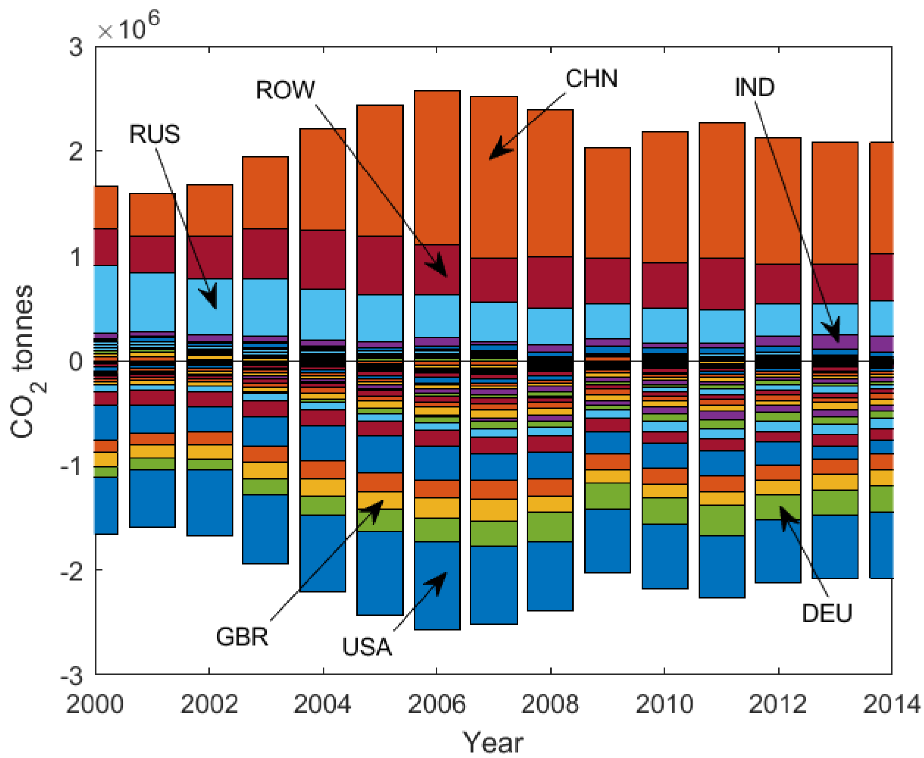

Figure 3: Emissions content of international trade, 2000–2014

When the drivers of net emissions exports are computed from equation (11), the results displayed in Figure 4 are obtained. According to these results, the principal driver of the emissions content of international trade is cross-country differences in efficiency levels. These findings are consistent with those of Douglas and Nishioka [8], although in the present study international differences in efficiency appear to play a somewhat smaller role. This is likely because, unlike Douglas and Nishioka [8], the present analysis isolates the effects of capital-augmenting and labour-augmenting technical change, so that efficiency here captures only total factor productivity, which is assumed to coincide with the productivity of pollution-abatement technology.

After international differences in efficiency, the next most important drivers of the emissions content of international trade are differences in emissions per efficiency unit and differences in output composition.

International differences in emissions per efficiency unit are likely related to cross-country differences in the ratio between pollution taxes and wages measured in efficiency units:

$$\frac{\tau}{w/\pi_L}$$

Under this interpretation, countries with high levels of emissions per efficiency unit are those in which pollution taxes are relatively low compared with productivity-adjusted wages. The data suggest that these policy differences may explain approximately one third of the emissions content of trade, insofar as producers in such countries devote fewer productive resources (capital and labour) to pollution-abatement activities.

Regarding international differences in output composition, Figure 4 shows that their contribution is smaller, although far from negligible. Moreover, their contribution is consistent with the predictions of the pollution haven hypothesis, as it is positive overall, indicating that part of the emissions content of international trade is explained by dirtier production structures in exporting countries and cleaner production structures in importing countries.

Figure 4 also shows that international differences in capital abundance play a negligible role in explaining the emissions content of trade. Although the technological variation tests reported previously indicate that capital abundance measured in efficiency units has a negative and statistically significant effect on emissions intensity, this effect does not appear to have been quantitatively important in the sample analysed. The reason is likely that capital per efficiency unit varies relatively little across countries and does so in a non-systematic manner. Consequently, both emissions-exporting and emissions-importing countries include economies that are either relatively capital-abundant or capital-scarce.

Finally, Figure 4 shows that the residual term plays only a limited role in explaining the drivers of the emissions content of international trade. On the one hand, this suggests that representation (2) provides a good description of the production techniques observed in the sample. On the other hand, it indicates that the residuals do not exhibit a systematic pattern affecting either imports or exports. This may imply that differences in product varieties within industries do not play a major role in explaining net emissions trade flows, as net exporters of emissions do not appear to specialise in systematically dirtier varieties of goods within each sector.

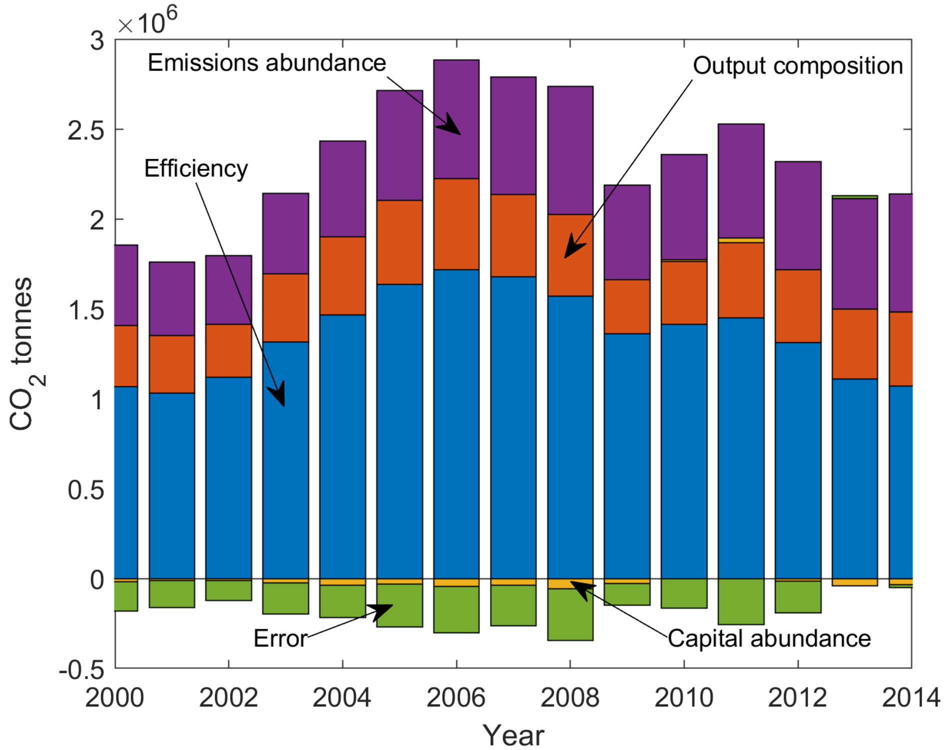

Figure 4: Drivers of the emissions content of international trade, 2000–2014

The structural decomposition in equation (11) also makes it possible to estimate how much each driver contributed to the increase in net emissions exports over the sample period. This is precisely what Figure 5 illustrates. Over the fifteen years covered by the sample, the principal driver behind the increase in emissions embodied in trade was the divergence in emissions per efficiency unit across countries. According to the interpretation discussed above, this may indicate that divergence in pollution-tax policies generated divergence in pollution-abatement effort, thereby increasing the net emissions content of North–South trade.

The second most important factor is the residual term, suggesting that an important share of the increase in net emissions exports cannot be fully accounted for by any of the four structural components considered. Finally, differences in output composition also appear to explain part of the increase in emissions embodied in trade. This may reflect the relocation of pollution-intensive industries toward potential pollution havens such as Russia or China.

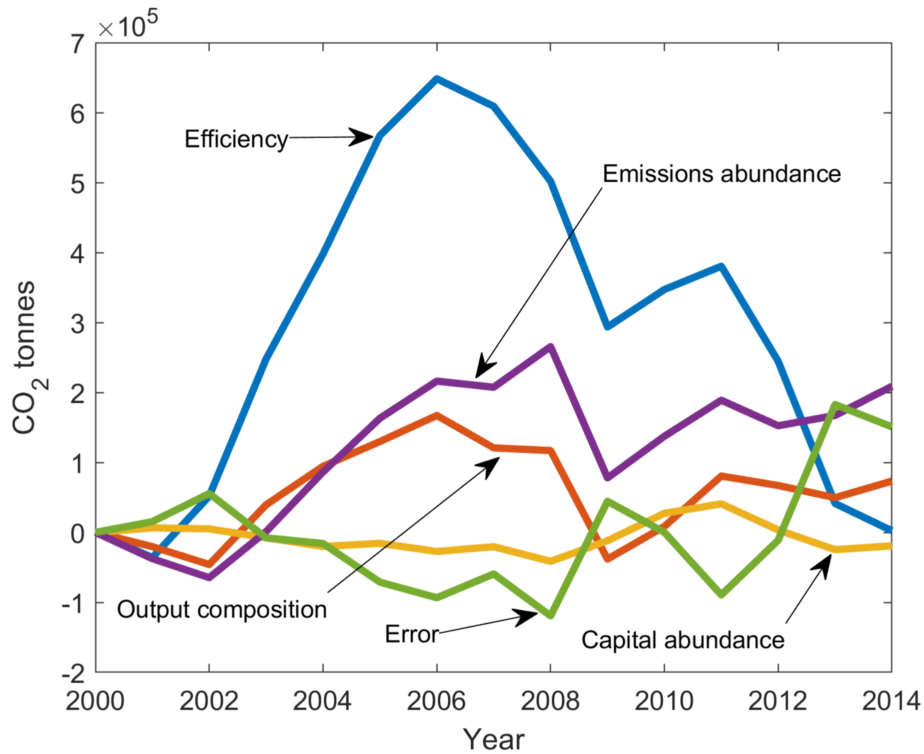

Figure 5: Drivers of the growth in emissions embodied in international trade, 2000–2014

In fact, the effect of output composition on the emissions content of trade is arguably the most relevant component, since it directly captures whether pollution-intensive industries tend to locate in pollution havens. The remaining factors are instead related to cross-country variation in production techniques arising from efficiency differences, factor endowments, or environmental policies. It is therefore worth examining this component in greater detail.

Figure 6 presents the emissions content of international trade attributable specifically to differences in output composition across countries. China, Russia, and the composite rest-of-the-world economy display relatively pollution-intensive production structures and are therefore net exporters of emissions. The opposite is true for countries such as the United States and the United Kingdom, whose cleaner production structures partly explain why they are net importers of emissions.

Nevertheless, Figure 6 also reveals some apparently paradoxical cases. Germany, for example, appeared in Figure 3 as a net importer of emissions, yet Figure 6 shows that its production structure is relatively pollution-intensive. Absent international differences in efficiency and environmental standards, Germany would in fact be a net exporter of emissions. The opposite occurs in the case of India, which is a net exporter of emissions primarily because its relatively low efficiency and weak environmental standards generate exceptionally high emissions per efficiency unit, despite having a comparatively clean production structure.

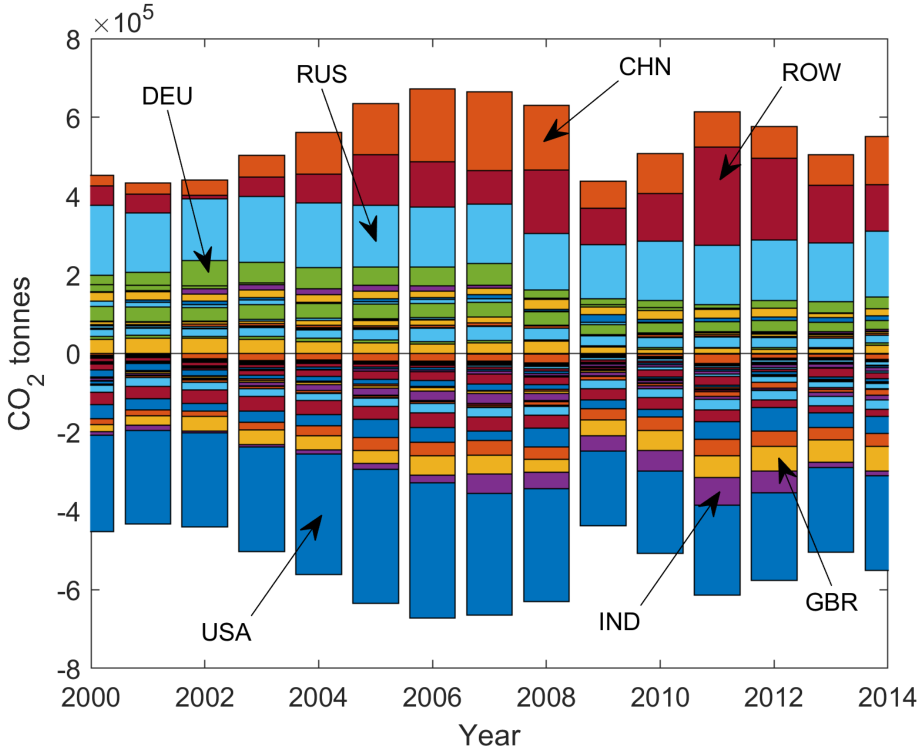

Figure 6: Emissions content of international trade attributable to differences in output composition, 2000–2014

This raises the following question: what is the relationship between emissions abundance and the contribution of output composition to the emissions content of trade? Emissions abundance is commonly measured as emissions per unit of GDP, although it could alternatively be measured as emissions per efficiency unit. Following the conventional approach, it is possible to construct a dimensionless variable measuring the relative abundance of emissions in country c:

$$\left(\frac{E_c/E_w}{Y_c/Y_w}\right) - 1 \tag{24}$$

where E_c denotes total emissions in country c, E_w total world emissions, Y_c GDP in country c, and Y_w world GDP. Values below zero indicate that emissions per unit of GDP in country c are lower than the world average, while values above zero indicate the opposite.

If the pollution haven hypothesis holds, it is reasonable to expect variable (24) to help explain the component of emissions embodied in trade attributable to output composition, once adjusted for country size. Accordingly, if equation (24) is treated as the exogenous variable, the endogenous variable may be defined as:

$$\frac{\phi_A^c / E_w}{Y_c / Y_w} \tag{25}$$

where ϕ_A^c denotes the portion of the emissions content of trade attributable to output composition in country c according to equation (11).

The question, therefore, is whether equation (25) is systematically related to equation (24). Figure 7 presents the corresponding scatter plot together with the fitted regression line, while Table 2 reports the results of several statistical tests, including those associated with the regression line represented in Figure 7.

According to the results reported in Table 2, it is not possible to reject the null hypothesis that emissions abundance, as measured by equation (24), is a poor predictor of the magnitude of the contribution of output composition to the emissions content of trade in equation (25). However, the results do allow rejection of the null hypothesis that equation (24) contains no relevant predictive information regarding the sign and relative ordering of equation (25).

Indeed, the regression analysis reveals a positive relationship between the two variables, although with only marginal statistical significance and limited explanatory power. By contrast, the non-parametric tests yield more encouraging results. In particular, the sign test, which measures the proportion of cases in which the sign of emissions abundance predicts the sign of the output-composition component of emissions embodied in trade, yields a result that can be rejected as purely random at the 99% confidence level. Specifically, in the sample analysed, approximately three out of every four countries in which the contribution of output composition to the emissions content of trade is positive (negative) are countries that are relatively abundant (scarce) in emissions.

Similarly, Kendall's rank correlation test, which evaluates whether high (low) values of emissions abundance tend to be associated with high (low) values of the output-composition component of emissions embodied in trade, rejects at the 95% confidence level the null hypothesis that no systematic relationship exists between the rankings of the two variables.

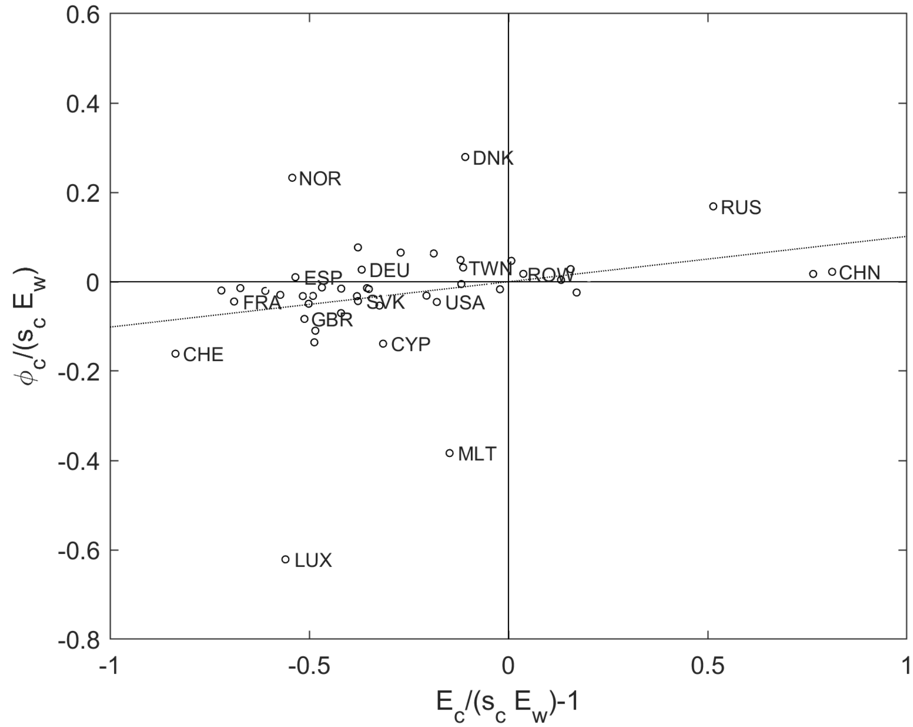

Figure 7: Relationship between emissions abundance and the output-composition component of emissions embodied in trade

Table 2: Tests of the Pollution Haven Hypothesis

Linear regression		
Slope	p-value	R^2
0.09 (0.04)	0.06	0.09
Sign test	Kendall rank test	
Statistic	Statistic	p-value
0.74	0.28	0.02

6 Conclusions and Policy Implications

This paper has developed a framework for analysing the emissions content of international trade in which emissions are treated as a joint product that can be mitigated through the allocation of productive resources to pollution-abatement activities. Within this framework, emissions-output coefficients were decomposed into components associated with general efficiency levels, capital abundance, emissions abundance per efficiency unit, and sector-specific production characteristics. This decomposition was subsequently incorporated into a structural decomposition analysis of the emissions embodied in international trade.

The empirical results indicate that the principal driver of the emissions content of trade is cross-country variation in efficiency levels. Countries with lower productivity levels tend to allocate productive resources less efficiently to pollution-abatement activities and therefore exhibit systematically higher emissions intensities across industries. At the same time, differences in emissions per efficiency unit — interpreted as reflecting differences in environmental standards and the relative cost of pollution — also play an important role, particularly in explaining the increase in emissions embodied in trade observed during the sample period.

By contrast, differences in capital abundance appear to have only a limited quantitative effect on the emissions content of trade. Although greater capital abundance reduces emissions intensity, cross-country variation in capital per efficiency unit is not sufficiently large or systematic to explain observed trade patterns. Differences in output composition also play a comparatively smaller role overall, although the empirical evidence remains broadly consistent with the pollution haven hypothesis. In particular, countries that are relatively abundant in emissions tend, on average, to display production structures that contribute positively to net emissions exports.

These findings have several policy implications. First, they suggest that environmental policies may influence the emissions content of trade even in the absence of major changes in production structure. Higher pollution taxes or stricter environmental standards increase the incentive to allocate labour and capital toward pollution-abatement activities, thereby reducing emissions intensity across industries. Consequently, environmental regulation affects not only the composition of output but also production techniques themselves.

Second, the results imply that technological progress and productivity growth may generate substantial environmental benefits. Improvements in efficiency increase the effectiveness of pollution-abatement activities and reduce the quantity of emissions generated per unit of output. Policies promoting technological diffusion, investment in cleaner production methods, and improvements in productive efficiency may therefore contribute significantly to reducing the emissions embodied in international trade.

Finally, although the evidence for the pollution haven hypothesis is weaker than often assumed in the literature, it cannot be dismissed entirely. Differences in output composition remain positively associated with emissions abundance, suggesting that pollution-intensive industries may indeed have some tendency to concentrate in countries with relatively weak environmental standards. This indicates that international coordination of environmental policies may be necessary in order to limit the relocation of pollution-intensive activities across countries.

Overall, the results suggest that the emissions content of international trade is shaped not by a single mechanism, but by the interaction between technological efficiency, environmental policies, and the international distribution of productive activities. Any comprehensive environmental strategy must therefore take all of these dimensions into account simultaneously.

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