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Global manufacturing SO_2 emissions: does trade matter?

Jean-Marie Grether · Nicole A. Mathys · Jaime de Melo

Abstract A growth-decomposition (scale, technique and composition effect) covering 62 countries and seven manufacturing sectors over the 1990–2000 period shows that trade, through reallocations of activities across countries, has contributed to a 2–3% *decrease* in world SO_2 emissions. However, when compared to a constructed counterfactual no-trade benchmark, depending on the base year, trade would have contributed to a 3–10% *increase* in emissions. Finally adding emissions coming from trade-related transport activities, global emissions are increased through trade by 16% in 1990 and 13% in 2000, the decline being largely attributable to a shift of dirty activities towards cleaner countries.

Keywords Embodied emissions in trade · Environment · Growth decomposition · Transport · World trade

JEL Classification F18 · Q56

J.-M. Grether (✉)
University of Neuchâtel, Pierre-à-Mazel 7, 2000 Neuchâtel, Switzerland
e-mail: jean-marie.grether@unine.ch

N. A. Mathys
Swiss Federal Office of Energy (Berne) and University of Neuchâtel,
Pierre-à-Mazel 7, 2000 Neuchâtel, Switzerland

J. de Melo
CERDI and CEPR, Départment d'économie politique,
University of Geneva, Uni Mail, 40 bd du Pont d'Arve,
1211 Genève 4, Switzerland

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1 Introduction

The last 30 years have witnessed a dramatic increase in manufacturing exports by developing countries, which lead to a deep structural change of trade patterns at the worldwide level. These shifts fuelled fears in environmentalist circles that world pollution would grow since it is generally admitted that lower income countries are characterized by lower environmental regulations (see for example Dasgupta et al. (1999)). In the trade and environment literature, this argument is usually known as the "pollution haven" (PH) *hypothesis*. It has been theoretically challenged, because even though less stringent (and poor) countries may specialize in polluting industries (according to the PH argument), capital abundant (and rich) countries tend to specialize in capital-intensive industries that also happen to be polluting, so that the net effect of trade expansion on pollution is generally unclear (see Copeland and Taylor (2004)). This theoretical ambiguity is paralleled by a large and growing empirical literature (see e.g. Cole and Elliott (2003b) for recent evidence based on both old and new trade models), and it is fair to say that the debate is still largely unsettled, because results are sensitive to data availability, empirical methodology and the type of pollutant considered.

Sulphur dioxide (SO_2) is a pollutant frequently analyzed because of its suitable characteristics: it is a by-product of goods production[1] with strong regional effects, available abatement technologies, and different regulations across countries. Moreover, a deeper understanding of SO_2 emissions contributes to a better understanding of three environmental problems: air pollution and smog, acid rain, and global climate change.[2] The SO_2 case is also a representative example of the methodological difficulties faced when analyzing the trade and environment nexus. One might say that the debate has been principally informed by studies following a rigorous (and useful) methodology, but applied to indirect and potentially relatively unrepresentative data [e.g. SO_2 concentrations rather than production-related emissions by Antweiler et al. (2001) or Frankel and Rose (2005), or economy-wide emissions rather than industry-specific ones as in Cole and Elliott (2003a)]. With the exception of the recent work by Levinson (2007), which is limited to the US case, a common feature of these studies is that their estimates of the link between emissions and trade is indirect, due to the lack of disaggregated data linking pollution directly to production and to the resulting trading activities.

This paper is an answer to the need for more direct and detailed evidence on the link between trade and SO_2 emissions at the worldwide level. Using new data assembled in a companion paper which details a large and consistent database of SO_2 manufacturing emission intensities that vary across *time*, *country* and *sector* (Grether et al. 2009), we analyze how trade, by reallocating labor and production across countries and sectors over time, affects the overall level of SO_2 emissions. The analysis of the impact of trade on emissions is in three steps. First, we carry out

[1] Manufacturing emissions account for approximately 45% of global anthropogenic SO_2 emissions, the rest being roughly split in half between power generation and other activities.

[2] As pointed out by Stern (2005), better data on SO_2 emissions give a more accurate picture of sulfate aerosols, which have a cooling effect and are an important contributor to climate change.

a growth-decomposition analysis based on observed worldwide changes in production and trade flows over the last decade. Second, we carry out a counterfactual analysis based on a constructed no-trade benchmark, no longer a temporal analysis, although the results depend on the year selected to construct the counterfactual benchmark. Third, we provide estimates of emissions due to trade-related transport activities. Together the three approaches give a more complete picture of the role of trade-related emissions.

In contrast to earlier studies, we cover a large number of countries and different manufacturing sectors allowing us to follow a bottom-up approach[3] at the worldwide level. The evidence is based on anthropogenic manufacturing emissions and their relationship with trade since our data do not include other types of emissions related to natural phenomena or non-traded activities (e.g. volcanic eruptions or household energy consumption). The disaggregated approach also helps to isolate the role of globalization on the intriguing downward trend in SO_2 emissions over the 1990–2000 periods. The paper shows that PH forces do exist, but that they have been declining over the whole sample period.

Section 2 reports growth-decompositions of SO_2 emissions for 62 countries (which account for over 75% of world emissions over the period), seven sectors (six "dirty" and one "clean" covering all remaining manufacturing sectors) and three base years (1990, 1995, 2000). Section 3 turns to the no-trade counterfactual while Sect. 4 takes into account trade-induced transport effects. Section 5 concludes.

2 Temporal decomposition 1990–2000

According to available estimates, world manufacturing SO_2 emissions have been falling during the 1990s. Was this obtained *thanks to* or *in spite of* increasing trade flows? Taking into account trade flows, this section identifies the technological and structural changes that have contributed to the reduction in global emissions. As trade allows countries with different polluting intensities to specialize over time, trade expansion may either increase or decrease world emissions depending on whether dirty production tends to be shifted towards dirtier or cleaner countries. Following a commentary on aggregate trends, we move on to a more systematic growth decomposition exercise into scale, composition and technique effects based on the disaggregated data. To our knowledge, it is the first time that such a decomposition exercise is performed at the worldwide level.

2.1 Data sources and aggregate trends

The paper relies on two main data sources. Trade flows, output and employment figures are from Nicita and Olarreaga (2007) while SO_2 emission intensities (i.e.

[3] By "bottom-up" we mean an analysis that is based on disaggregated emission and economic activity data instead of performing a "top-down" approach where information on structural changes is inferred from regression analysis performed on aggregate data.

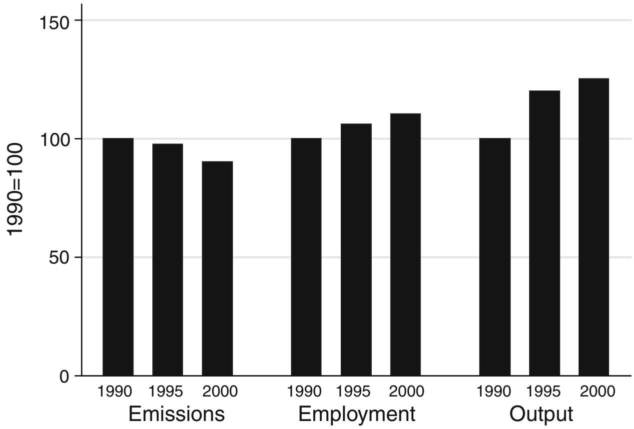

Fig. 1 Global trends in manufacturing emissions, employment and output (1990 = 100)

kilograms of SO_2 per employee or per dollar) which vary across time, sector and country are from our companion paper.[4]

Figure 1 presents the evolution of SO_2 emissions, output and employment in the manufacturing sector at the world level. The contrast is striking between the decline in manufacturing emissions by 10%, while employment and output are concurrently rising by 10 and 20% respectively. Overall, manufacturing became a lot cleaner at the worldwide level.

Three reasons for this decline in emission are reviewed in the different panels of Fig. 2. Figure 2a shows an increase in the output share of clean products.[5] However, employment shares follow an opposite trend, suggesting that the explanation is more complex and linked to differences in productivity gains between "clean" and "dirty" sectors.

A second possibility would be that, contrarily to what is feared by environmentalists, production could have shifted towards cleaner countries. Splitting the sample into a "North" and "South" group in Fig. 2b gives ammunitions to the environmentalists: the share of the South is rising, particularly for employment, which increases from 50 to almost 60% across the sample period. Thus, although it remains to be confirmed that Southern countries are indeed dirtier (see below), the global shift towards cleaner countries seems an even more inadequate explanation than the previous one.

[4] These data are based on the combination of three data sets: the Emission Database for Global Atmospheric Research (henceforth EDGAR), compiled by Olivier and Berdowski (2001) and Olivier et al. (2002), the Industrial Pollution Projection System of the World Bank (see Hettige et al. (1995)) and the recent estimates of Stern (2006). Two particular adjustments were necessary to combine these data sets. First, as Stern's national estimates take better abatement activities into account, they were used to adjust the original EDGAR emission intensities by proportional scaling. Second, we completed the output and employment figures which are missing in the original data of Nicita and Olarreaga (2007) by using a simple imputing procedure.

[5] Unlike the specific convention followed in the rest of this paper, the definition of "clean" and "dirty" products used to construct Fig. 2a is based on the more usual classification of the 28 ISIC-3 digit sectors into five clean, 5 dirty and 18 "in-between" categories (e.g. Copeland and Taylor (2003)).

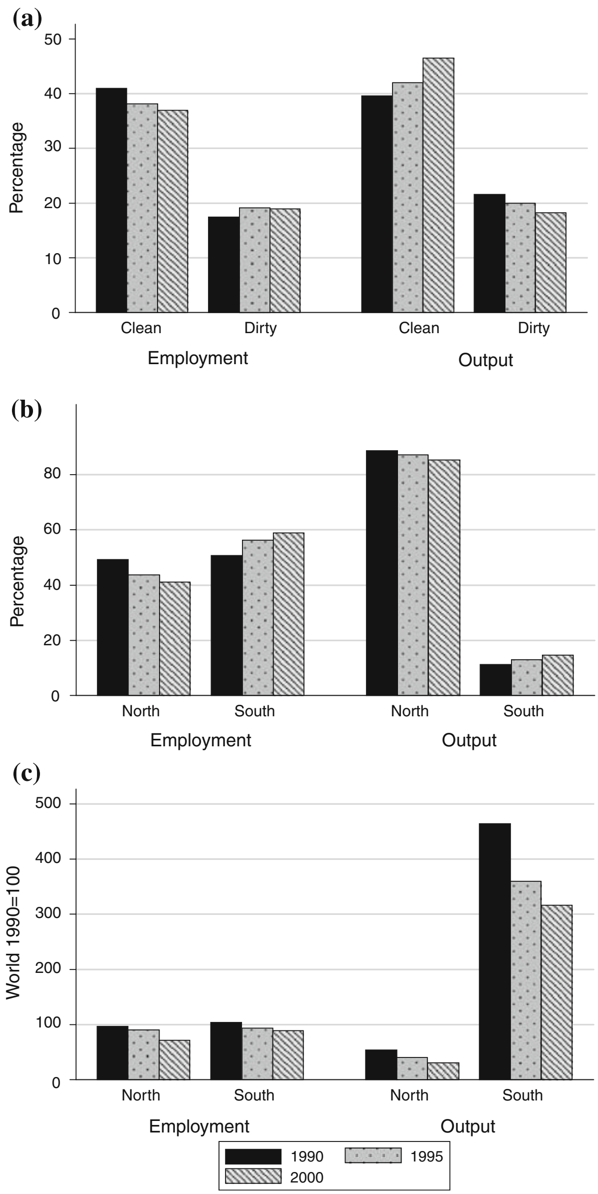

Fig. 2 Three alternative explanations of the fall in SO_2 emissions. **a** Employment and output shares for clean and dirty sectors; *Clean sectors* ISIC 3-digit sectors 321 and 382-385, *Dirty sectors* ISIC 3-digit sectors 341, 351, 369, 371 and 372. **b** Employment and output shares for North and South; *North* United States, Canada, high income Asia and Europe, *South* Latin America, Africa and low income Asia. **c** Emission intensities for North and South

So we are left with the third explanation: a shift towards cleaner technologies. Figure 2c is consistent with this view, as it shows that the average emission intensity (whether manufacturing activity is measured by output or labor) is declining for both North and South. Note also that the difference in levels between North and South is quite striking when intensity is measured in terms of emissions per unit of output, with emission intensity about five times higher in the South and the relative gap remaining roughly constant. However, most of this gap seems to be due to productivity differences: when measured in terms of emissions per unit of labor, Northern and Southern emission intensities look a lot more similar.

So far, it appears that the major force behind the decline in manufacturing emissions has been technical progress, which seems to have affected both poor and rich countries alike. Moreover, this technique effect has been stronger than the scale effect, as global emissions have declined in spite of the increase in both indicators of manufacturing activity. Only the more disaggregated decompositions that follow can confirm (or infirm) these preliminary conclusions.

2.2 Scale, technique and (two) composition effects

As in Grossman and Krueger (1991), we present formulas that identify the importance of the scale, technique and composition effects identified in the literature. Define emissions per unit of employment (rather than per unit output) to capture the scale effect by total employment (rather than total output).[6] Let then L_{kit} represent employment in activity k in country i, year t, and γ_{kit} the emission intensity per unit of labor. Then the resulting SO_2 emissions (E) at the sector, country and global levels are given by:

$$E_{kit} = \gamma_{kit} L_{kit};\ E_{it} = \sum_k \gamma_{kit} L_{kit};\ E_t = \sum_k \sum_i \gamma_{kit} L_{kit}. \qquad (1)$$

For each country, national emissions can be decomposed into a scale (changes in manufacturing employment), composition (changes in the allocation of labor across sectors) and technique effect (changes in emission intensity per unit labor). The same decomposition carries across countries (adding another source of composition effect, across countries this time). To this end, world emissions (E_t) have first to be rewritten as the product of world manufacturing employment (L_t) times world average emission intensity, the latter being a weighted average across all countries:

$$E_t = L_t \sum_i \phi_{it}^{L_t} \bar{\gamma}_{it}, \qquad (2)$$

where $\phi_{it}^{L_t}$ is the share of country i in world employment, $\phi_{it}^{L_t} \equiv \frac{L_{it}}{L_t}$,[7] and $\bar{\gamma}_{it}$ is country i's average emission intensity, $\bar{\gamma}_{it} \equiv \frac{E_{it}}{L_{it}}$.

[6] Using labor instead of output as the scaling variable leads to lower scale and technique effects (as productivity gains are excluded) but hardly affects the order of magnitude of the composition effects which are the focus here (see our companion paper for further discussion of the relative merits of each scaling factor and comparisons under the two approaches).

[7] The following notational convention is used: $\phi_v^{Z_w}$ is the share of Z_v in the aggregate Z_w, where v,w = kit,kt,it and Z = L,E. For example, $\phi_{it}^{E_t}$ is the share of country i in global emissions, $\phi_{it}^{E_t} \equiv \frac{E_{it}}{E_t}$.

Using a "^" to denote percentage changes and neglecting interaction terms (which are uniformly allocated to main effects in the application), total logarithmic differentiation of (2) yields (3) which shows that global growth of SO_2 emissions can be decomposed into a *scale* effect, $\hat{L}_t$, a *between-country* effect, $\sum_i \phi_{it}^{E_t} \left(\widehat{\phi_{it}^{L_t}}\right)$, and a *within-country* effect, $\sum_i \phi_{it}^{E_t} \left(\widehat{\bar{\gamma}_{it}}\right)$:

$$\hat{E}_t = \hat{L}_t + \sum_i \phi_{it}^{E_t} \left(\widehat{\phi_{it}^{L_t}}\right) + \sum_i \phi_{it}^{E_t} \left(\widehat{\bar{\gamma}_{it}}\right). \tag{3}$$

The average country intensity can also be written as a weighted average of sectoral intensities, with weights given by the share of each sector in national manufacturing employment, i.e. $\bar{\gamma}_{it} = \sum_k \phi_{kit}^{L_{it}} \gamma_{kit}$ $\left(\phi_{kit}^{L_{it}} \equiv \frac{L_{kit}}{L_{it}}\right)$. Thus, the third term in Eq. (3) can be decomposed further, leading to the final expression:

$$\hat{E}_t = \hat{L}_t + \sum_i \phi_{it}^{E_t} \left(\widehat{\phi_{it}^{L_t}}\right) + \sum_k \sum_i \phi_{kit}^{E_t} \left(\widehat{\phi_{kit}^{L_{it}}}\right) + \sum_k \sum_i \phi_{kit}^{E_t} \left(\widehat{\gamma_{kit}}\right). \tag{4}$$

. In (4), the third term on the RHS represents the *between-sector* effect and the fourth the *technique* effect. This last expression is the most complete, but its application is conditioned to the availability of data at the sector level. Below, we present results of the decomposition first for the national level data used by previous authors [i.e. Eq. (3)], then for the disaggregated manufacturing data assembled here (i.e. Eq. (4)).

2.3 Decomposition results

Table 1 applies the decomposition from (3) to the aggregate data and time periods used by Cole and Elliott (2003a) and Stern (2005).[8] In this Table, the within-country effect lumps together the between-sector and technique effects. All decompositions are in broad agreement showing a reduction in emissions, and the results are very close when there is period (1980–1990) and sector overlap. This is because the sample used by Cole and Elliott (2003a) includes all the major emitters present in Stern's sample. Comparing our results with those in Stern (2005) over the period 1990–2000 indicates larger differences. This is probably because Stern's economy-wide estimates capture the Engel-related shift of activities from manufacturing to largely non-polluting service activities.

Two further comments are in order. First, apart from the 1960–1970 period, all studies reflect negative between-country and within-country effects that help mitigate the impact of the strong scale effect. This suggests that the composition effects brought up by trade throughout the period have not been so devastating. One possible explanation is that pollution-generating activities being largely weight-

[8] We also tried without success to apply this decomposition to the SO_2 concentration data of Antweiler et al. (2001). However, we failed to convert these concentration data into emission data because the link between the two is too complex and data demanding (see for an example Schichtel (1996)). Indeed, when we used the method proposed by Giannitrapani et al. (2006) to recover emission data from the concentration data, the regression lacked explanatory power.

Table 1 Comparison of SO_2 growth decomposition across different data sets (%)

Data set	Period	Number of countries	Sector[a]	Scale effect	Between-country effect	Within-country effect	Total effect[b]
This study	1990–2000	62	Manufacturing	9.51	−2.36	−17.00	−9.85
Cole and Elliott (2003)	1980–1990	26	Economy-wide	21.70	−6.64	−16.71	−1.65
	1975–1990			33.60	−9.93	−24.87	−1.25
Stern (2005)	1960–1970	146	Economy-wide	20.79	−4.73	15.43	31.49
	1970–1980			23.13	−6.48	−7.82	8.83
	1980–1990			22.28	−6.74	−17.06	−1.52
	1990–2000	144		15.47	−3.86	−33.52	−21.92
	1960–2000			89.50	−19.36	−60.45	9.68

See Eq. 3 for decomposition formula. All effects are expressed in percentage points

[a] This study is restricted to manufacturing-related emissions while the other studies contain total anthropogenic emissions (coming from manufacturing, transport, heating, …)

[b] Total effect = scale effect + between-country effect + within-country effect

reducing, the scope for PH patterns has been rather limited, resulting in quite effective pollution-reduction policies.[9] Second, the Stern data by decade indicate that the turning point for SO_2 emissions took place in the 1980s and that the main driving factor behind this reversal is the within-country effect, which becomes negative in the 1970s and ever stronger since then. This may hide both a shift towards cleaner activities and the adoption of cleaner techniques, which we now try to disentangle.

Application of (4) in the first line of Table 2 shows that the large within-country effect (17%) contributing to a decline in emissions identified before works mainly through the greening of production technologies as the technique effect reduced emissions by 14% over the 1990–2000 period. The trends identified here are difficult to reconcile with a "PH view" of the world. If PH forces were prevalent, one would expect a global shift of manufacturing labor towards dirtier countries and dirtier activities (as labor productivity tends to be smaller in dirty countries) coupled with few incentives to adopt cleaner technologies.

The small significance of PH forces is confirmed when the decomposition is carried-out separately for exports and for domestic use (bottom part of Table 2).[10] Exports, which accounted for 22% of emissions in 1990, contributed significantly both to the growth in emissions because of the increasing share of trade in manufacturing (80%) but also to the decline in emissions through the composition effects (between country and between sector). This pattern confirms that export growth was concentrated in the cleanest sectors. Here again, if PH forces were

[9] Based on a gravity model, Grether and de Melo (2004) provide evidence that "dirty" industries have higher transport costs than "clean" industries.

[10] Labor is allocated by end use in proportion of output. In Table 2, the total effect of the first line is equal to the emission-weighted average of the total effects of the second and third lines, but this property does not extend to the other effects.

Table 2 Scale, composition and technique effects (percent)

	Shares in 1990		Total effect	Decomposition of total effect			
	Labor share	Emission share		Scale	Between country	Between sector	Technique
Total effect[a]	100	100	−9.85	9.55	−2.44	−3.03	−13.94
Decomposition by end use							
Domestic use	79.40	77.38	−19.17	−12.61	−1.86	11.88	−16.57
Exports	20.60	22.62	22.00	80.80	−19.66	−32.57	−6.57

[a] Slight differences in results with those in Table 1 come from the inclusion of one additional interaction term. The total effect is a weighted average of the different end use effects where emission shares are used as weights

strong, the between-sector effect would be negative for domestic use and positive for exports, the opposite of the observed pattern.

These aggregate results are based on summing the elements of (4) over 62 countries and seven sectors (434 combinations). Hence it is natural to identify influential countries and sectors by grouping together the relevant combinations. Figure 3 ranks the countries (Fig. 3a) and activities (Fig. 3b) that account for the bulk of the change in emissions. We concentrate here on absolute effects to isolate the combinations of sectors and countries that have experienced the largest (be it positive or negative) structural change in SO_2 emissions. Figure 3a lists 12 countries that account for three quarters of the cumulative effects. Except for Chile, Peru and India, all countries contribute to a decline in emissions. The right-hand panel carries out the same decomposition as in Table 2. We find negative technique effects for all countries but for the three mentioned above and also large technique effects for China (−10%) and Germany (−3.3%).[11] Figure 3b reports the ranking for the six dirty industries and the residual “clean” sector. Looking at the net contribution to the decline in emissions, the leading sectors are petroleum and coal products, followed by chemicals and iron and steel, with most of the contribution to the decline coming from the adoption of cleaner technologies. Non-ferrous metal stands out as the only sector with a strong net growth in emissions.

These findings are broadly confirmed when the results are reported at the most disaggregated level (see Table A6 in Grether et al. (2007)). Among the most influential commodity-country combinations, Chile and Peru stand out with a positive rather than negative technique effects for their copper smelting activities.[12] Non-ferrous metal is also the most influential sector in China.

[11] These estimated magnitudes for China should be interpreted with caution, since the emission totals are computed from official statistics which are believed to exaggerate the reduction in intensities (see Stern (2005: 170) for a discussion of differences in estimates across sources).

[12] Although Olivier et al. (2002) indicate that SO_2 emission for non-ferrous metals have a large uncertainty estimate, it is clear that this sector is an important contributor to SO_2 emissions and that Chile is the world’s largest producer (see for example Anthony et al. (2004)). Miketa and Mulder (2005) have shown that this sector is also the only one where energy productivity divergence has been observed, while Newbold (2006) stresses recent efforts to implement environmental systems, leaving hope for a negative technique effect after 2000.

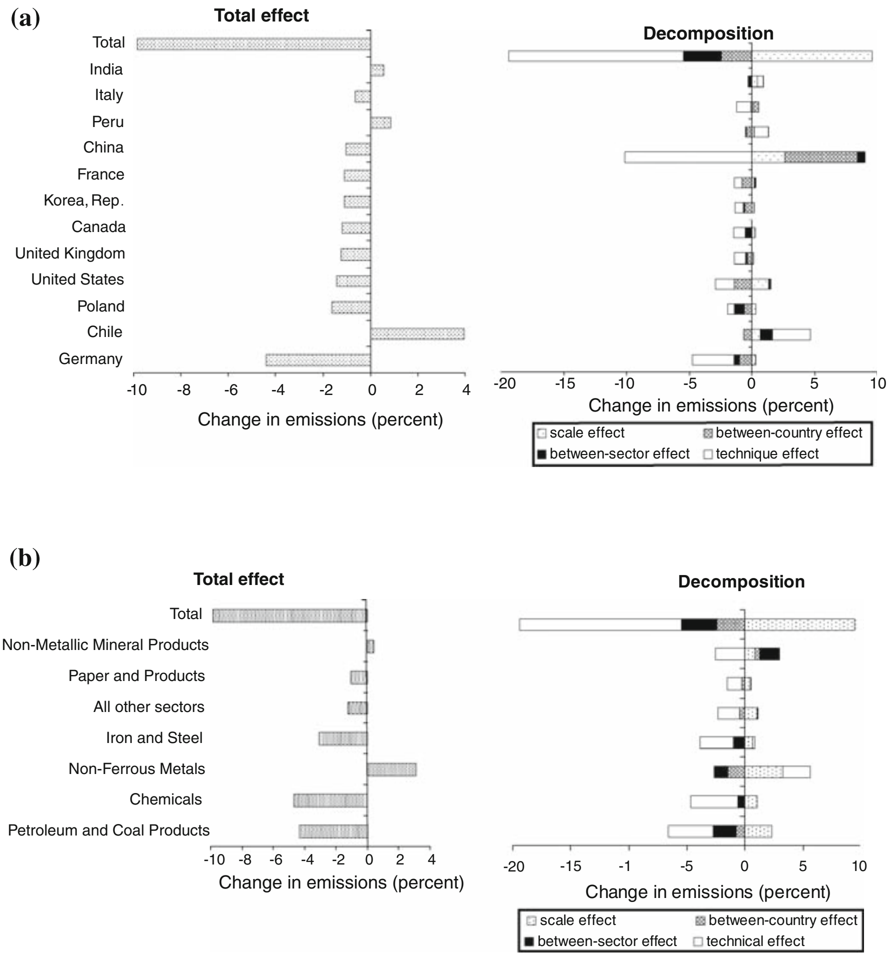

Fig. 3 Growth decomposition by country and sector. **a** Contribution of each country to total effect (ranked by decreasing absolute total effect) **b** Contribution of each sector to total effect (ranked by decreasing absolute total effect)

Summing up, the decompositions suggest that the (temporal) reallocation of production brought by trade (or between-country effect in our framework) has led to a small reduction (around 2–3%) rather than to an increase in SO_2 emissions at the world level. This result is quite robust across databases and should mitigate the fears raised by environmentalists. However, to get a fuller sense of trade-related effects, one must move beyond a temporal analysis and carry out a counterfactual analysis based on a no-trade benchmark.

3 Would autarky be any cleaner?

By allowing production to be decoupled from consumption, trade leads to a different level of world emissions than in a no-trade situation. To this effect, we construct a simple no-trade anti-monde and compare it with the emissions observed with the actual production and trade figures.

3.1 A simple no-trade benchmark

Define a simple no-trade benchmark in which each country now produces what it was importing under the (observed) trade equilibrium. This line of reasoning abstracts from resource constraints or price effects in order to focus on the interaction between trade patterns and emission intensity differences. If the cleanest countries tend to be the largest importers of dirty goods, then trade will tend to increase global emissions, by shifting dirty production towards dirty countries, much along the lines of the PH hypothesis. However, this very direct estimate should be taken with a grain of salt, since the great bulk of trade in dirty products comes from natural-resource-based products, which, by definition, are not subject to comparative advantage, and could not be produced locally (e.g. France would probably not be able to produce its observed consumption of copper products). In sum, this simple approach provides, at best, suggestive first-order effects that would have to be extended by building a no-trade anti-monde using general equilibrium techniques.[13]

Take then sector k in country i year t, and denote local production by Q_{kit}, domestic (so-called "apparent") consumption by C_{kit}, and exports (imports) by X_{kit} (M_{kit}), all values being expressed in current dollars. Neglecting inventories, $Q_{kit} + M_{kit} = C_{kit} + X_{kit}$. This relationship, however, will not hold for emissions to the extent that imports (and thus parts of consumption) are produced with a different technology. To estimate ΔE_t, the change in production-embodied emissions, generated by a shift from the autarkic to the trade situation, we compute the change in embodied emissions when production shifts from the apparent consumption level, $C_{kit} = Q_{kit} + M_{kit} - X_{kit}$, to the actual production level, Q_{kit}. Let then g_{kit} represent SO_2 emissions per unit dollar, while ℓ_{kit} represents labor productivity, so that the relationship between per dollar and per unit labor intensities is $g_{kit} = \gamma_{kit}/\ell_{kit}$. The change in emissions at the sector level becomes:

$$\Delta E_{kit} = g_{kit}Q_{kit} - g_{kit}C_{kit} = g_{kit}(X_{kit} - M_{kit}), \tag{5}$$

which means that the change in emissions generated by trade is just equal to the trade balance times the corresponding domestic intensity coefficient. Aggregating across sectors:

$$\Delta E_{it} = \bar{g}_{it}^{X} X_{it} - \bar{g}_{it}^{M} M_{it}, \tag{6}$$

where $\bar{g}_{it}^{X} = \sum_k \phi_{kit}^{X_{it}} g_{kit}$ ($\bar{g}_{it}^{M} = \sum_k \phi_{kit}^{M_{it}} g_{kit}$) is the average export (import) intensity of country i (we extend the convention of the $\phi_v^{Z_w}$ notation to $Z = X,M,Q$). To bring out the role of trade, it is convenient to also aggregate (5) across countries. Straightforward manipulations lead to the following expression for the change in world emissions for sector k:

[13] See also Antweiler (1996) for the inclusion of input-output relationships in a similar context.

$$\Delta E_{kt} = M_{kt} n \sigma_{kt}, \tag{7}$$

where M_{kt} is world imports (or exports) of good k ($M_{kt} = \sum_i M_{kit}$), n is the number of countries in the world, and σ_{kt} is the covariance between pollution intensity and the difference between the export and the import share of country i in world imports of good k, i.e. $\sigma_{kt} = \text{cov}\left(\frac{X_{kit} - M_{kit}}{M_{kt}}; g_{kit}\right)$. The expression shows that, apart from the role of scaling factors (n,M,g), the trade-induced change in world emissions will be particularly large if the countries with the largest trade deficits also tend to be the cleanest ones. This is consistent with intuition and the PH view, so we name this covariance term the *PH covariance*.

We can now aggregate either (6) or (7) to obtain the total change in emissions at the worldwide level, ΔE_t. For comparison purpose, we scale this change by worldwide emission levels in autarky, $E_t = \bar{g}_t^C C_t$, where C_t is apparent consumption and $\bar{g}_t^C$ is the world average pollution intensity, $\bar{g}_t^C = \sum_k \sum_i \phi_{kit}^{C_t} g_{kit}$. This leads to the following expressions:

$$\frac{\Delta E_t}{E_t} = \frac{\sum_i \Delta E_{it}}{E_t} = \frac{X_t}{C_t} \frac{\left[\bar{g}_t^X - \bar{g}_t^M\right]}{\bar{g}_t^C}, \tag{8a}$$

$$\frac{\Delta E_t}{E_t} = \frac{\sum_k \Delta E_{kt}}{E_t} = \frac{X_t n \bar{\sigma}_t}{C_t \bar{g}_t^C}, \tag{8b}$$

where $X_t = M_t$ is total exports or imports, $\bar{g}_t^X = \sum_i \phi_{it}^{X_t} \bar{g}_{it}^X$ ($\bar{g}_t^M = \sum_i \phi_{it}^{M_t} \bar{g}_{it}^M$) is the world average emission intensity in exports (imports) and $\bar{\sigma}_t$ is the world average PH covariance ($\bar{\sigma}_t = \sum_k \phi_{kt}^{M_t} \sigma_{kt}$). Both expressions reflect the fact that trade exacerbates emissions when the largest importers of the most polluting products are also the cleanest producers. Both expressions also show that the impact of trade on world emissions corresponds to the product between an average trade openness ratio (X_t/C_t) and a PH ratio (either $\bar{g}_t^X - \bar{g}_t^M$ or $n\bar{\sigma}_t$ divided by $\bar{g}_t^C$). But while (8a) is helpful to identify those countries with the largest contribution to the overall change, (8b) is more convenient to identify the sectors that play the most important role.

3.2 Counterfactual estimates

Table 3 summarizes the results of this counterfactual applied to 1990 and 2000. As shown in the first line of the Table, under this scenario where apparent consumption is replaced by observed production, opening up to trade leads to an increase of roughly 10% in emissions in 1990. Interestingly, the corresponding estimate for 2000 shows a much smaller increase of 3.5%. On the one hand, subject to the caveat that much of trade in pollution-intensive products is natural-resource-based trade, this supports the PH view. Indeed, the average PH covariance is positive for both years, which means that the largest net exporters tend to be the dirtiest producers. However, on the other hand, and perhaps more importantly, the results also show that the PH pattern has almost vanished over time. The decrease in the PH ratio, by more than 75% over 10 years, is particularly dramatic, and even more so when one

Table 3 Impact of trade on world emissions and its decomposition

	Formula[a]	Effect	1990	2000	Change (%)
(a)(b)	$\frac{\Delta E_t}{E_t}$	Total emission change (%)	9.75	3.35	–66
(a)	$\frac{X_t}{C_t}$	Trade openness ratio	0.20	0.29	+46
(b) = (c)/(d)	$\frac{n\bar{\sigma}_t}{\bar{g}_t^C}$	PH ratio	0.49	0.12	–77
(c) = (e) − (f)[b]	$n\bar{\sigma}_t$	PH covariance	1.52	0.26	–83
(d)[b]	$\bar{g}_t^C$	Average pollution intensity	3.12	2.28	–27
(e)[b]	$\bar{g}_t^X$	Average export pollution intensity	4.76	2.72	–43
(f)[b]	$\bar{g}_t^M$	Average import pollution intensity	3.24	2.46	–24

[a] See Eqs. (8a) and (8b) in the text

[b] Expressed in g/USD

takes into account the decrease by more than 25% of the average pollution intensity (which appears in the denominator of the PH ratio).

Disaggregated results confirm the above patterns and help identify the largest contributors to the overall effects (see Tables A7–A9 in Grether et al. (2007)). When the contribution is positive, it is of the PH type, while it is of the "green-haven" type when the contribution is negative. Regarding countries first, the most preeminent pollution havens in both periods are Chile, South Africa and Peru, while China is a green haven and Indonesia switches from PH in 1990 to green haven in 2000. Regarding sectors, the most influential ones are non-ferrous metals, a strong PH contributor in both periods, and petroleum and coal products, which switch from pollution to green havens over the sample period.

In short, the counterfactual analysis suggests that the observed world with trade is in accordance with the PH argument, i.e. trade leads to an increase in world SO_2 emissions compared to the no-trade benchmark. However, the 1990s witnessed both a general shift towards cleaner technologies and a relative shift of dirty production towards cleaner countries. Both shifts strongly reduced the PH pattern that characterized the beginning of the period. As a result, at the end of the period, even if trade intensity had increased, the PH bias had shrunk so much that the net contribution of trade to global emissions has been reduced by two-thirds. Note, however, that since trade, by promoting growth, would also increase emissions, these first-order effects may represent a lower bound.

4 Transport-related emissions

A discussion of the role of trade on emissions would be incomplete if transport-related emissions were not factored in. Surprisingly, emissions directly emitted by international transport are not analyzed in the current trade and environment literature, while it is one of the main arguments of anti-globalization activists. Consider then the following back-of-the-envelope calculations based on three transport modes (rail, road and ships) and on a range of estimates to account for the

Table 4 Emissions from international shipments

	SO_2 emission coefficient (g/tkm)			Share in world shipments (percent of tkm)
	Lower		Upper	
A. Transport mode				
Rail[a]	0.07		0.18	12
Road[a]	0.10		0.43	14
Ship[b]	0.19		0.52	74
				100
Average emission coefficient (g/tkm)	0.16		0.47	
			1990	2000
B. Shipments[c]				
Shipment volume (billion tonnes)			0.37	0.46
Shipment (trillion tkm)			2.01	3.81
Shipment value (trillion current USD)			6.54	9.68
C. Transport related emissions (percent)[d]		Lower	2.77	4.50
		Upper	8.15	13.32
		Average	5.46	8.91
Trade-related emissions (percent)[e]			9.75	3.35

[a] From OECD (1997)

[b] Network for Transport and Environment (NTM calc, 2003)

[c] Distance data comes from CEPII (2006), mode shares for 1995 from the EC (1999)

[d] Percent of worldwide production-related emissions

[e] Report of the first line of Table 3

diversity of available sources of average SO_2 emissions per tonne-km (tkm) shipped.[14]

International shipment estimates are reported in the middle part of Table 4.[15] Results show an increase in tonnage, value and in tkm tonnage. The increase in tkm translates into a similar increase in transport-related emissions. As a result, the share of transport-related emissions in total production-related emissions increases over the period (see bottom part of Table 4). Taking the average estimates, international trade-related transport emissions have accounted for about 5–9% of worldwide manufacturing-related production emissions of SO_2. Comparing these figures with those of Table 3 suggests that transport-related emissions have gone from accounting for roughly one third to three quarters of total trade-related emissions across the 1990–2000 period. To put it differently, if we add up emissions coming

[14] The variability of transport-related emissions is only cross-sectional due to data availability. The share of airplanes in terms of manufacturing tkm shipments is so small that it can be neglected as a transport mode.

[15] International distance between the most important agglomerations has been corrected by the average distance between producers and consumers for each country. This takes into account the fact that, if there were no trade, goods would be shipped anyway within each country from producers to consumers.

from trade-related composition effects and trade related transport activities, we obtain that global worldwide manufacturing emissions are increased through trade by 16% in 1990 and 13% in 2000, i.e. the strong decline in the PH pattern identified in the previous section is almost eaten away by the increase in transport-related emissions.

Any interpretation of these results should however be taken with caution. We only dispose of transport data information for 1995, while one would expect that composition (transport mode changes), scale (increase in global tkm) and technique effects (decrease in emission intensities per tkm) have also taken place for the transport sector between 1990 and 2000.

5 Conclusions

Combining data from different sources to obtain country, sector and year-specific pollution coefficients and "taking the data seriously", this paper investigates the role of trade in worldwide SO_2 manufacturing. First, decompositions into scale, composition and technique effects show that the increase in manufacturing activities is roughly compensated by a decline in (per unit of labor) emissions due to the adoption of cleaner production techniques. Second, about one-fifth of the "within-country" effect (i.e. when sector-level data are not available) is in fact due to a shift towards cleaner industries (the rest corresponding to the technique effect). Third, the aggregate composition effects are (negative and) small with respect to the scale effect, which suggests that the PH hypothesis debated in the trade and environment literature, has only had a limited impact, at least over this period. These orders of magnitude, which are directly obtained from disaggregated data rather than inferred from regression exercises, deserve attention per se because they help weigh the relative importance of the scale effect vis-à-vis other effects, which work in the opposite direction and are often neglected in the public debate. Besides, the by-sector and by-country estimates also help identify "pollution havens" versus "green havens", and hence where to direct emission-reduction Pigovian efforts.

This growth-decomposition analysis of the role of trade is extended by estimates based on a constructed no-trade anti-monde. First, compared to a no-trade benchmark in which every country has to produce locally what it is actually importing, observed international trade increased emissions by 10% in 1990, but only by 3.5% in 2000. Thus large net importers tend to be clean countries in 1990 but this PH pattern looses its importance over time. Second, back-of-the-envelope estimates of emissions related to transport activities are added to these estimates. Given the increase in international transport, related emissions have almost doubled over the sample period. Adding up trade (compared to autarky) and trade-related transport emissions, worldwide manufacturing emissions increased by 16% in 1990 and by 13% in 2000 compared to the hypothetical no-trade benchmark.

Several caveats are in order. On the data side, enlarging the sample to more countries and pollutants, or increasing the disaggregation level would all be desirable. On the methodological side, our first-order estimates do not control for price effects, input-output relationships or the endogeneity of trade and environmental policies, all of which are likely to be of practical importance. These effects could be taken into account relatively easily in a multi-country general equilibrium simulation model which would also be an appropriate setting to study the effects of Pigovian taxation. Both extensions should be the focus of forthcoming efforts.

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