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Werner Antweiler
Brian R. Copeland
M. Scott Taylor

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ABSTRACT

This paper sets out a theory of how openness to international goods markets affects pollution concentrations. We develop a theoretical model to divide trade's impact on pollution into scale, technique, and composition effects and then examine this theory using data on sulfur dioxide concentrations from the Global Environment Monitoring Project. We find international trade creates relatively small changes in pollution concentrations when it alters the composition, and hence the pollution intensity, of national output. Our estimates of the associated technique and scale efforts created by trade imply a net reduction in pollution from these sources. Combining our estimates of scale, composition, and technique efforts yields a somewhat surprising conclusion: freer trade appears to be good for the environment.

Werner Antweiler
Policy Division, Faculty of Commerce
University of British Columbia
Vancouver, BC V6T 1Z1
CANADA
werner@pacific.commerce.ubc.ca

Brian R. Copeland
Department of Economics
997-1873 East Mall
University of British Columbia
Vancouver, BC V6T 1Z1
CANADA
copeland@econ.ubc.ca

M. Scott Taylor
Department of Economics
University of Wisconsin
Social Science Building 6448
1180 Observatory Dr.
Madison, WI 53706-1393
and NBER
staylor@ssc.wisc.edu

1. Introduction

The debate over the role international trade plays in determining environmental outcomes has at times generated more heat than light. Theoretical work has been successful in identifying a series of hypotheses linking openness to trade and environmental quality, but the empirical verification of these hypotheses has seriously lagged. Foremost among these is the pollution haven hypothesis that suggests relatively low-income developing countries will be made dirtier with trade. Its natural alternative, the simple factor endowment hypothesis, suggests that dirty capital intensive processes should relocate to the relatively capital abundant developed countries with trade. Empirical work by Grossman and Krueger (1993), Jaffe et al. (1995) and Tobey (1990) cast serious doubt on the strength of the simple pollution haven hypothesis because they find trade flows are primarily responsive to factor endowment considerations and apparently not responsive to differences in pollution abatement costs. Does this mean that trade has no effect on the environment?

This paper sets out a theory of how "openness" to international goods markets affects pollution levels to assess the environmental consequences of international trade. We develop a theoretical model to divide trade's impact on pollution into scale, technique and composition effects and then examine this theory using data on sulfur dioxide concentrations from the Global Environment Monitoring Project. The decomposition of trade's effect into scale, technique and composition effects has proven useful in other contexts [see Grossman and Krueger (1993), Copeland and Taylor (1994,1995)] and here we move one step forward to provide estimates of their magnitude. We find that international trade creates relatively small changes in pollution concentrations when it alters the composition, and hence the pollution intensity, of national output. Combining this result with our estimates of scale and technique effects yields a somewhat surprising conclusion: if trade liberalization raises GDP per person by 1%, then pollution concentrations fall by about 1%. In the case of sulfur dioxide concentrations, free trade is good for the environment.

We obtain this conclusion by estimating a very simple model highlighting the interaction of factor endowment and income differences in determining the pattern of trade. Our approach, while relatively straightforward, is novel in three respects. First, by exploiting the panel structure of our data set, we are able to distinguish empirically between the negative environmental consequences of scalar increases in economic activity - the scale effect - and the positive environmental consequences of increases in income that call for cleaner production methods - the technique effect. This distinction is important for many reasons.[1] Our estimates indicate that a 1% increase in the scale of economic activity raises concentrations by approximately .3%, but the accompanying increase in income drives concentrations down by approximately 1.4% via a technique effect.

Second, we devise a method for isolating how trade-induced changes in the composition of output affects pollution concentrations. Both the pollution haven hypothesis and the factor endowment hypothesis predict openness to trade will alter the composition of national output in a way that depends on a nation's comparative advantage. For example in the pollution haven hypothesis, poor countries get dirtier with trade while rich countries get cleaner.[2] As a result, looking for a consistent relationship between additional pollution and openness to trade (across a panel of both rich and poor countries) is unlikely to be fruitful. Instead we look for trade's composition effect after conditioning on country characteristics. We find that openness per se, measured in a variety of ways, has very little consistent impact on pollution concentrations. Openness conditioned on country characteristics has however a highly significant, but relatively small, impact on pollution concentrations.

And lastly, our approach forces us to distinguish between the pollution consequences of income changes brought about by changes in openness from those created by capital accumulation or technological progress. We find that income gains brought about by further trade or neutral technological progress tend to lower pollution, but income gains brought about by capital accumulation raise pollution. The key difference is that capital accumulation favors the production of pollution intensive goods whereas neutral technological progress and further trade do not. One immediate implication of this finding is that the pollution consequences of economic growth are dependent on the underlying source of growth. Another more speculative implication is that pollution concentrations should at first rise and

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[1] For example, income transfers across countries raise national income but not output, whereas foreign direct investment raises output more than national income. For these, and many other reasons, we need separate estimates of technique and scale effects.

[2] That is, the composition effect of trade for poor countries makes them dirtier while the composition effect for rich countries makes them cleaner. The full effect of trade may be positive even for poor countries depending on the strength of the technique and scale effects.

then fall with increases in income per capita, if capital accumulation becomes a less important source of growth as development proceeds.

The theoretical literature on trade and the environment contains many papers where either income differences or policy differences across countries drive pollution intensive industries to the lax regulation or low-income country. For example, Pethig (1976), Siebert et al. (1980), and McGuire (1982) all present models where the costs of pollution intensive goods are lower in the region with no environmental policy. One criticism of these papers is that while they are successful in predicting trade patterns in a world where policy is fixed and unresponsive, their results may be a highly misleading guide to policy in a world where environmental protection responds endogenously to changing conditions. Empirical work by Grossman and Krueger (1993) suggests that it is important to allow policy to change endogenously with income levels and in our earlier work (Copeland and Taylor (1994, 1995)) we incorporated the Grossman-Krueger finding to investigate how income-induced differences in pollution policy determine trade patterns.

While this earlier work produced several insights, it was limited because it ignored the potential role factor abundance could play in determining trade patterns. In contrast, the model we develop here allows income differences and factor abundance differences to jointly determine trade patterns. This extension is important, especially in an empirical investigation, because many of the most polluting industries are also highly capital intensive.[3]

The empirical literature in this area has progressed in three distinct ways. First, there are studies that primarily concern themselves with growth and pollution levels and interpret their results as indicative of the relative strength of scale versus technique effects (for example, Grossman and Krueger (1993, 1995), Shafik (1994), Seldon and Song (1994), Gale and Mendez (1996), and Dean (1998)). Many of these studies also add a measure of openness as an additional explanatory variable. There is a second group of studies that examines how trade flows may themselves be affected by the level of abatement costs or strictness of pollution regulation in the trading partner countries. This approach was pioneered by Tobey (1990), and then employed in the context of the NAFTA agreement by Grossman and Krueger (1993) and for a large cross section of countries by Antweiler

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[3] See appendix B, section B.1 for evidence linking capital intensity and pollution intensity.

(1996). Finally there are those studies that employ the U.S. Toxic Release Inventory to infer how changes in production and trade flows has altered the pollution intensity of production in both developed and developing countries. Work along these lines includes Low and Yeats (1992).

Overall the results from these studies are best described as mixed. Apart from specific case studies, there is very little evidence linking liberalized trade in general with significant changes in the environment. In addition, there is little evidence that differences in abatement costs are a significant determinant of trade flows. There is, however, evidence that increases in income will, after a point, lead to lower concentrations of some pollutants. But the role that trade plays in this process is not entirely clear. Finally, there is some evidence that the composition of exports of some developing countries have become dirtier over time but these results follow only from a relatively narrow set of toxic pollutants recorded in the U.S. inventory.

Ideally an empirical investigation should be able to distinguish between the negative environmental consequences of scalar increases in economic activity - the scale effect - and the positive environmental consequences of increases in income that call for cleaner production methods - the technique effect. Grossman and Krueger and others interpret their hump-shaped Kuznets curve as reflecting the relative strength of scale versus technique effects, but they do not provide separate estimates of their magnitude.[4] As well, an empirical investigation should be able to identify how trade affects average pollution intensity of national output by altering its composition. Many studies include some measure of openness in their regressions to capture a composition effect, but there is very little reason to believe that openness per se affects the composition of output in all countries in the same way. Without a measure of the compositional effects of trade, we cannot assess whether trade's real income gains come at the cost of a dirtier mix of national production. Finally, many of the existing studies have a very weak theoretical base and this makes inference difficult. Without a causal mechanism linking trade to consequent changes in the environment it is difficult to isolate the effects of trade on the environment from other factors such as

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[4] Moreover we would argue income per capita is not an appropriate measure of scale, and hence the Grossman-Krueger finding does not reflect the relative strength of scale and technique effects. Gale and Mendez (1996) separate scale and technique effects by using city population figures, but their method is not entirely satisfactory. See section 3.2 for further discussion.

technological changes in abatement activity, capital accumulation, or other sources of real income change.

We would be the first to admit that our simple theoretical model carries a heavy burden in providing us with the structure needed to isolate and identify the implications of international trade. We suggest however that earlier empirical investigations failed to find a strong link between environmental outcomes and freer trade precisely because they lacked a strong theoretical underpinning. With a more coherent theoretical framework we are able to look in the "right directions" for trade's effect.

The remainder of the paper is organized as follows. In section 2 we outline our theory and in section 3 we describe our empirical strategy. In section 4 we present our empirical results estimating trade’s effect on pollution. Section 5 concludes. Appendix A contains summary statistics for data, plus additional notes on data sources and methods. Appendix B contains some additional supporting materials. In Appendix C we report results from a series of sensitivity tests of our specification.

2. Theory

2.1. The model

A population of N agents lives in a small open economy that produces two final goods, X and Y, with two primary factors, labor, L, and capital, K. Industry Y is labor intensive and does not pollute. Industry X is capital intensive and generates pollution as a by-product. We assume constant returns to scale, and hence the production technology for X and Y can be described by unit cost functions $c^X(w,r)$ and $c^Y(w,r)$. We let Y be the numeraire, set $p_y = 1$, and denote the relative price of X by p.

By choice of units, 1 unit of pollution is generated for each unit of X produced. We call this the base level of pollution and denote it by B. Producers have access to an abatement technology however, which for simplicity we assume uses only good X as an input. For a given base level of pollution B, the amount of pollution abated, A, is given by the function $\lambda A(x_a,B)$, where x_a is the amount of resources allocated to abatement. We will treat λ as a parameter that may be affected by technological change. *Pollution emissions* are then given by B minus A, or:

$$z = [x - \lambda A(x_a,x)]. \tag{2.1}$$

We assume $A(x_a,x)$ is linearly homogeneous, increasing, and concave in x_a and x. Hence we can write

$$A(x_a,x) = xa(\theta), \tag{2.2}$$

where $\theta = x_a/x$ is the fraction of X output devoted to abatement, and $a(\theta) \equiv A(\theta,1)$. We assume there is no abatement without inputs, and that it is not possible to fully abate all pollution: i.e. $a(0) = 0$ and $\lambda a(1) < 1$. Note our specification implies increasing marginal abatement costs since, for a given level of base pollution, there are diminishing returns to abatement activity.

Using (2.2), we can rewrite pollution emissions (2.1) as

$$z = x[1 - \lambda a(\theta)]. \tag{2.3}$$

Producers

We can now specify the equilibrium conditions for the production side of the economy. We assume the government uses pollution emission taxes (which are endogenous) to reduce pollution. Given the pollution tax τ, the profits π^x for a firm producing X are given by revenue, less production costs, pollution taxes, and abatement costs:

$$\pi^x = px - c^x(w,r)\,x - \tau[1 - \lambda a(\theta)]x - p\theta x. \tag{2.4}$$

Firms will jointly choose gross output (x) and their abatement fraction θ to maximize profits. Define

$$\tilde{p} = p(1 - \theta) - \tau[1 - \lambda a(\theta)].$$

Then (2.4) becomes:

$$\pi^x = \tilde{p}\,x - c^x(w,r)x.$$

Because of constant returns to scale, the output of an individual firm is indeterminate, but for any level of output, the first order condition for the choice of θ implies

$$p = \lambda\tau a'(\theta). \tag{2.5}$$

(2.5) implicitly defines the optimal abatement θ as an increasing function of τ/p:

$$\theta = \theta(\lambda\tau/p), \tag{2.6}$$

where $\theta' > 0$. As one would expect, abatement activity is increasing in the level of the pollution tax.

With free entry, firms will enter each industry until profits are zero. Using (2.4), we have for the X industry

$$c^x(w,r) = \tilde{p} \tag{2.7}$$

and for the Y industry, we have

$$c^Y(w,r) = 1. \tag{2.8}$$

We assume both industries are active, and hence (2.7) and (2.8) determine factor prices w and r as functions of $\tilde{p}$. Factor prices in turn determine the unit input coefficients for each sector. For example, by Shepherd's Lemma, the unit labor requirement in X is given by $c_w^x \equiv \partial c^x/\partial w$, etc. The full employment conditions then determine outputs:

$$c_w^x\, x + c_w^Y\, y = L \tag{2.9}$$

$$c_r^x\, x + c_r^Y\, y = K \tag{2.10}$$

where, as noted before, x denotes gross output of X. Net output of X (that remaining for consumption and/or export) is $x_n = x - x_a = x(1 - \theta)$.

Consumers

Each consumer maximizes utility, treating pollution as given. For simplicity, we assume preferences over consumption goods are homothetic and the marginal disutility of pollution is constant. The indirect utility function of a typical consumer is given by

$$V(p,G/N,z) = u\left(\frac{G/N}{\rho(p)}\right) - \delta z, \tag{2.11}$$

where G is national income (so G/N is per capita income), ρ is a price index, u is increasing and concave, and δ is the marginal disutility of pollution. Note that pollution is harmful to consumers and is treated as a pure public bad (all consumers experience the same level of pollution).

It is convenient to define real per capita income as

$$I \equiv \frac{G/N}{\rho(p)} \quad , \tag{2.12}$$

and rewrite the indirect utility as $u(I) - \delta z$.

Government

Pollution policy is determined by the government, and will vary with economic conditions. We model the policy process very simply by assuming the government sets a pollution tax, and that the level of the tax is an increasing function of the optimal tax. This allows for the possibility that government behavior varies across countries (perhaps depending on country characteristics and political systems), but also allows pollution policy to respond endogenously to changing economic conditions.

Since all consumers are identical, the optimal pollution tax maximizes the sum of utilities:

$$\max_{\{\tau\}} \left\{ N[u(I) - \delta z] \right\} .$$

The solution to this problem yields

$$\tau \quad = N\,\delta\varphi[p,I], \tag{2.13}$$

where $\varphi = \rho(p)/u'$, and $\varphi_I > 0$ since u is concave. $\delta\varphi[p,I]$ can be interpreted as marginal damage per person, and hence (2.13) is just the standard Samuelson rule. The pollution tax is the sum of marginal damages across all individuals and is increasing in real income because environmental quality is a normal good.

The actual pollution tax τ is assumed to be an increasing function T of the optimal tax τ^*:

$$\tau = T(\tau\ ), \tag{2.14}$$

where $T' > 0$, $T(\tau\ ) \leq \tau$, and we assume $\varepsilon_{T,\tau} \leq 1$. T depends on variables (suppressed here) that reflect the responsiveness of the government to the efficient policy. If policy is always optimal, then the elasticity of T with respect to the optimal tax, $\varepsilon_{T,\tau} = 1$.

The equilibrium level of pollution can now be determined by substituting (2.14) and (2.6) into (2.3), and then using the market clearing conditions (2.7) - (2.10) to determine output levels.

2.2. Scale, technique and composition effects

Because the relationship between economic activity and environmental quality is complex, it is useful to begin by decomposing the total effect of a change in pollution into scale, composition, and technique effects. To investigate further, define the scale of economic activity S as the value of the economy's gross output at world prices:[5]

$$S = px + y. \tag{2.15}$$

To define the composition effect it is convenient to work with x/y ratios. Let $\chi = x/y$ denote the relative supply of X. Solving (2.9) and (2.10) for x and y and dividing yields

$$\frac{x}{y} = \frac{c_w^Y \kappa - c_r^Y}{c_r^x - c_w^x \kappa} \equiv \chi(\kappa, \tilde{p}), \tag{2.16}$$

where $\kappa = K/L$ is the economy's capital labor ratio. Note that χ is increasing in κ and $\tilde{p}$; and therefore increasing in p and decreasing in τ.[6] We will refer to any change in the economy that alters $\chi(\kappa,\tilde{p})$ as creating a composition effect. Using (2.15) and (2.16), we can now rewrite our expression for pollution (2.3) as:

$$z = \frac{[1 - \lambda a(\theta)]\chi S}{1+p\chi} \quad . \tag{2.17}$$

To obtain our decomposition, totally differentiate (2.17) to yield:[7]

$$\hat{z} = \hat{S} + \phi_y \hat{\chi} - \zeta\, \varepsilon_{a,\theta}\, \hat{\theta} \tag{2.18}$$

where "^" denotes "percent change", $\phi_y = y/(px+y)$ is the share of y in the value of gross output, $\varepsilon_{a,\theta}$ is the elasticity of a with respect to θ, and $\zeta = \lambda a(\theta)x/z$ is the ratio of abated

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[5] There are other ways of defining scale. We need a quantity index, and (2.15) is convenient for our purposes.

[6] To confirm this, note that $\chi = x/y$ is increasing in $\tilde{p}$, and that (using 2.5), $d\tilde{p}/dp = 1-\theta > 0$, and $d\tilde{p}/d\tau = -(1-\lambda a(\theta)) < 0$.

[7] We hold world prices and the abatement technology constant throughout this section. Section 2.3 considers changes in world prices and trade frictions.

pollution to actual pollution. The first term is the scale effect. Holding constant pollution abatement techniques and the mix of goods produced, an increase in the scale of economic activity will raise pollution. Next is the composition effect. Holding scale and techniques constant, a shift in the composition of production towards more pollution intensive goods will raise pollution. Finally, the technique effect: holding the scale and composition of economic activity constant, pollution levels will fall in response to an increase in the intensity of pollution abatement.

According to (2.18), the observed variation in our pollution data arises from variation in the scale, composition and techniques of economic activity across countries and over time. We will adopt a quantity index of output to proxy for scale in our empirical work. To relate the composition and technique effects to observable variables as well, we differentiate (2.16) and (2.6) to obtain expressions for $\hat{\chi}$ and $\hat{\theta}$ which we then substitute into (2.18). This yields

$$\hat{z} = \hat{S} + \phi_y \varepsilon_{\chi,k} \hat{\kappa} - (\phi_y \alpha_\tau \varepsilon_{\chi,\tilde{p}} + \zeta \varepsilon_{a,\theta} \varepsilon_{\theta,\tau}) \hat{\tau} \qquad (2.19)$$

where ε_{ij} denotes the elasticity of i with respect to j, and $\alpha_\tau = \tau\lambda[1-a(\theta)]/\tilde{p}$. Since we do not observe policy directly in our data set, we must replace $\hat{\tau}$ in (2.19) with its determinants. From (2.13) and (2.14) we can write $\hat{\tau}$ as:

$$\hat{\tau} = \varepsilon_{T,\tau} [\hat{N} + \varepsilon_{\varphi,I} \hat{I} + \hat{\delta}]. \qquad (2.20)$$

The pollution tax depends on population size, real per capita income, and consumer tastes. Now substitute (2.20) into (2.19), to obtain:

$$\hat{z} = \gamma_1 \hat{S} + \gamma_2 \hat{\kappa} - \gamma_3 \hat{I} - \gamma_4 \hat{N} - \gamma_5 \hat{\delta}, \qquad (2.21)$$

where $\gamma_1 = 1$, $\gamma_2 = \phi_y \varepsilon_{\chi,k} > 0$, $\gamma_3 = \varepsilon_{\varphi,I} \gamma_4 > 0$, $\gamma_4 = \varepsilon_{T,\tau} (\phi_y \theta_\tau \varepsilon_{\chi,\tilde{p}} + \zeta \varepsilon_{a,\theta} \varepsilon_{\theta,\tau}) > 0$, and $\gamma_5 = \gamma_4 > 0$.

The first term in (2.21) is the scale effect, as before. The second term measures the effect on pollution of an increase in the capital/labor ratio. This is a composition effect. Since the polluting industry is capital intensive, a more capital abundant country generates more pollution, all else equal. The remaining terms all reflect the effects of changes in pollution policy; we will refer to them as technique effects.[8] An increase in the level of per

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[8] In fact, because an increase in τ also reduces $\tilde{p}$ (the producer price of x), the technique effect is always reinforced by an induced composition effect. But for simplicity, we shall simply refer to the effects of policy changes as a technique effect.

capita income increases the demand for environmental quality, and leads to stricter pollution policy ($\varepsilon_{\varphi,I} > 0$); an increase in the number of people exposed ($\hat{N} > 0$) leads to stricter pollution policy via the Samuelson rule; and an increase in the marginal disutility of pollution ($\hat{\delta} > 0$, which may arise from increased knowledge about pollution) will also increase the demand for environmental quality and increase the pollution tax. Finally it is worthwhile to note the strength of these last three technique effects depends on $\varepsilon_{T,\tau}$, which indexes the government responsiveness to the preferences of the representative agent.

Equation (2.21) neatly summarizes our predictions about how pollution varies across countries and over time in response to observable variables (holding prices and the abatement technology fixed). Pollution rises with the scale of the economy and capital abundance. Increases in income, the marginal disutility of pollution, and the number of people exposed to pollution lead to a tightening of policy and a reduction in pollution. Equation (2.21) is not a suitable basis for estimation however because we have held both world and domestic prices fixed in its derivation.

2.3. Increased openness

To examine the consequences of increased openness on pollution levels, suppose transport costs or other frictions act as a barrier to trade. Given a common world price p^w, the domestic price in any country can be written,

$$p = \beta p^w$$

where β measures the importance of trade frictions. Note $\beta > 1$ if a country imports X and $\beta < 1$ if a country exports X.[9] We refer to a movement of β towards 1 as an increase in openness, or freer trade. Referring again to (2.18), recall that any change in the economy (including an increase in openness) generates scale, technique and composition effects. In deriving (2.21) we held domestic prices fixed. If we now allow for both trade frictions and world prices to change we have

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[9] For example, let υ be the level of iceberg transport costs (that is $\upsilon < 1$ is the fraction of the good that arrives at the destination when a unit is exported). Then if the good is exported from home, we have $p^d = \upsilon p^w$, and if the good is imported, we have $p^d = p^w/\upsilon$. Freer trade (an increase in υ) raises p^d if x is exported and lowers p^d if x is imported.

$$\hat{p} = \hat{\beta} + \hat{p}^{w}.$$

Amending (2.21) yields:

$$\hat{z} = \gamma_1\hat{S} + \gamma_2\hat{\kappa} - \gamma_3\hat{I} - \gamma_4\hat{N} - \gamma_5\hat{\delta} + \gamma_6\hat{p}^{w} + \gamma_7\hat{\beta} \qquad (2.22)$$

where $\gamma_6 = \gamma_7 = \phi_y\varepsilon_{\chi,\tilde{p}} + \zeta\,\varepsilon_{a,\theta}\varepsilon_{\theta,\tau}(1 - \varepsilon_{T,\tau}\,\varepsilon_{\varphi,p}) > 0$.[10] The remaining γ_i are as defined previously. As before, pollution varies with scale, capital abundance, income levels, etc. but as well, pollution now also varies with world prices and trade frictions.

Equation (2.22) is very important to our subsequent analysis because it establishes one key result and naturally leads to a discussion of how we identify the impact of trade in our empirical work. The key result contained in (2.22) is simply that a reduction in trade frictions will affect different countries in different ways. We should not expect to find openness *per se* related in any systematic way to pollution. This follows because β rises with freer trade for an exporter of the polluting good and β falls for an importer. While the coefficient of $\hat{\beta}$ is positive, an increase in openness yields $\hat{\beta} > 0$ for a country with a comparative advantage in dirty goods, and $\hat{\beta} < 0$ for a country with a comparative advantage in clean goods. We summarize these results in Proposition 1.

Proposition 1. Consider two economies which are identical, except with respect to openness (that is, they have the same scale, per capita income, population, tastes, technology, and relative factor abundance). (a) Suppose that both countries export the polluting good. Then pollution is higher in the country that has lower trade frictions. (b) Suppose that both countries import the polluting good. Then pollution is lower in the country that has lower trade frictions.

Proof: Suppose country 1 has lower trade frictions than country 2. In case (a), we have $\beta_1 < \beta_2$. In case (b) we have $\beta_2 < \beta_1$. Now apply (2.22).

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[10] The result that $\gamma_6 > 0$ requires a restriction on $\varepsilon_{T,\tau}$. A sufficient condition for $\gamma_6 > 0$ is that $\varepsilon_{T,\tau}\,\varepsilon_{\varphi,p} \leq 1$. From Roy's Identity and the definition of φ following (2.13), we have $\varepsilon_{\varphi,p} = \phi_{xc} < 1$, where ϕ_{xc} is the share of x in consumption spending. If policy is always perfect or if the government is less than fully responsive to changes in the optimal tax, then $\varepsilon_{T,\tau} \leq 1$, and the result follows.

The means by which a country is made cleaner or dirtier works through its impact on domestic relative prices. When $\hat{\beta} > 0$ (or when $\hat{p}^w > 0$) the relative price of the pollution intensive good rises. Holding the abatement intensity constant, an increase in the relative price of X stimulates the output of X, and hence increases pollution via this composition effect. Second, for given levels of the pollution tax, an increase in the price of X increases the cost of abatement activity and this also increases pollution. When $\hat{\beta} < 0$ (or when $\hat{p}^w < 0$) just the opposite occurs.

While all countries in our sample will respond similarly to a change in world prices, their response to a change in trade frictions depends on their comparative advantage. This feature of our theory provides a method for identifying the composition effect created by freer trade. It suggests that some of the variation in our pollution data could be explained by a country's openness, but only after we have conditioned on those country characteristics that determine comparative advantage.

It is important to recognize that a fall in trade frictions or change in world prices alters both the scale of economic activity and income per capita in addition to those changes mentioned above. As a result, the full impact of a reduction in trade frictions is not captured by the coefficient on $\hat{\beta}$. The $\hat{\beta}$ term is a trade-induced composition effect, holding scale and per capita income fixed. A full accounting of the impact of further openness would have to take into account the induced scale and technique effects as well as any trade-induced composition effect. Totally differentiating (2.17) with respect to β, holding all else except trade frictions constant yields:

$$\hat{z} = \gamma_1\hat{S} - \gamma_3\hat{I} + \gamma_7\hat{\beta}$$

A fall in trade frictions results in an increase in economic activity and this scale effect increases pollution. There will also be an increase in real per capita income creating a technique effect. And finally, there is the composition effect discussed previously. We will not attempt to measure how a reduction in trade frictions alters either the scale of economic activity or income per capita in our empirical work. The scale of the economy and real per capita income are influenced by many factors in addition to openness to trade. Identifying the separate influence of trade on growth and on static income levels is the subject of an already voluminous, and somewhat controversial, literature. Our strategy is to provide a direct estimate of the composition effect created by an increase in openness by controlling for scale and per capita income. We also provide estimates linking the scale of economic activity and income levels to pollution concentrations. We then use economic theory to tell us how to combine our estimates of scale, technique and (trade-induced) composition effects in order to assess the environmental consequences of freer trade.[11]

The pattern of trade

Proposition 1 tells us that looking for a simple correlation between openness and environmental quality is unlikely to be fruitful. Rather, we have to focus on the link between openness, comparative advantage, and pollution. Hence we need to take study the factors determining a country's comparative advantage. In our model, comparative advantage is determined by the interplay of relative factor endowments and differences in pollution policy, (which are mainly due to differences in per capita income). To investigate the determinants of comparative advantage we solve for autarky relative prices.

Because preferences over consumption goods are homothetic and there are constant returns to scale in production we can use relative supply and demand curves to determine autarky prices. Recalling that p denotes the relative price of good x, let RD(p) denote the demand for good x relative to good y. Then the autarky relative price of good x is determined by the intersection of the (net) relative supply and demand curves

$$RD(p) = (1-\theta)\chi(\kappa,\tilde{p}) \qquad (2.23)$$

where the gross relative supply $\chi = x/y$ is defined by (2.16), and net relative supply is $(1-\theta)\chi$. Totally differentiating and using (2.13), we obtain an expression showing how autarky prices vary with income and endowments:

$$\hat{p} = \frac{-\varepsilon_{\chi,\kappa}\hat{\kappa} + \varepsilon_{T,\tau}\varepsilon_{\varphi,I}\left[\alpha_{\tau}\varepsilon_{\chi,\tilde{p}} + \zeta\varepsilon_{\theta,\tau}\right]\hat{I}}{\Lambda}, \qquad (2.24)$$

where $\Lambda = \alpha_p\varepsilon_{\chi,\tilde{p}} + \zeta\,\varepsilon_{\theta,\tau} - \varepsilon_{T,\tau*}\varepsilon_{\varphi,p}[\alpha_\tau\varepsilon_{\chi,\tilde{p}} + \zeta\,\varepsilon_{\theta,\tau}] - \varepsilon_{RD,p} > 0$.

The pattern of trade is determined by the interaction of two influences: relative factor abundance and pollution policy. Pollution policy in turn is influenced by income. To show how each of these factors affect comparative advantage let us consider them separately.

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[11] See section 4.3.

The role of factor endowments

Standard factor endowment theories predict that capital abundant countries should export capital intensive goods. In our model this need not be true because pollution policy can potentially reverse the pattern of trade. Nevertheless, capital abundance is still one of the key determinants of comparative advantage in our model. Because X is relatively capital intensive, an increase in κ, holding all else constant, increases Home's relative supply of X, and lowers Home's autarky relative price of X. [Using (2.24), we obtain $\hat{p} < 0$ since $\varepsilon_{\chi,\kappa} > 0$]. All else equal, an increase in the relative abundance of the factor used relatively intensively in the pollution intensive sector should increase the likelihood that a country will be an exporter of pollution intensive goods. More concretely, we can show that if the country is *sufficiently* capital abundant, it must export the capital intensive (polluting) good:

Proposition 2. Suppose the world price p is fixed. Then, for a given level of income I, there exists $\underline{\kappa}$ such that if $\kappa > \underline{\kappa}$, then Home exports X. Moreover, for such a country, the pure composition effect of trade liberalization will be to increase pollution.

Proof. For a given p and I, Home's relative demand RD(p) is fixed. Relative supply χ is given by (2.16) for the case where the economy is diversified in both goods. For given p and I, the unit input coefficients in (2.11) are fixed, and hence χ approaches infinity as κ rises. Consequently, there exists some $\underline{\kappa}$ such that for $\kappa > \underline{\kappa}$, χ exceeds relative demand, and hence Home exports X. The increase in pollution via the composition effect follows from Prop. 1.

The role of income differences

An alternative theory of trade patterns is the *pollution haven hypothesis*. According to this view, poor countries have a comparative advantage in dirty goods because they have relatively lax pollution policy, and rich countries have a comparative advantage in clean goods because of their stringent pollution policy.[12] This result can be obtained as a special case of our model: if all countries have the same relative factor endowments, but differ in per capita incomes, then indeed richer countries will have stricter pollution policy and this will lead to a comparative advantage in clean goods. When countries differ in factor endowments as well, then we can obtain a weaker result: if a country is sufficiently rich, holding all else constant, then it will export the clean good.

As before, we begin by determining domestic prices prior to trade. Consider the effects of increasing income in a country, holding relative factor abundance constant. In this case, (2.24) reduces to

$$\hat{p} = \frac{\varepsilon_{T,\tau}\ \varepsilon_{\varphi,I}\left[\alpha_\tau \varepsilon_{\chi,\tilde{p}} + \zeta\varepsilon_{\theta,\tau}\right]\hat{I}}{\Lambda}, \tag{2.25}$$

Since environmental quality is a normal good, we have $\varepsilon_{\varphi,I} > 0$. Hence we conclude from (2.25) that $\hat{p} > 0$. In autarky, the relative price of the pollution intensive good rises with per capita income if we control for relative factor abundance. Hence high income, all else equal, tends to generate a comparative disadvantage in pollution intensive goods. More concretely, we can show that if the country is *sufficiently* rich, it must export the labor intensive (clean) good.

Proposition 3. Suppose the world price p is fixed and there exists $\underline{\varepsilon}$ such that $\varepsilon_{\varphi,I} > \underline{\varepsilon} > 0$. Then, for a given level of the capital/labor ratio κ (and holding all else constant), there exists $\underline{I}$, such that if $I > \underline{I}$, then Home exports Y. Moreover, for such a country, the pure composition effect of trade liberalization will be to reduce pollution.

Proof: The relative price of x facing producers is $\tilde{p} = p(1 - \theta) - \tau\lambda(1 - a(\theta)) < p(1 - \theta) - \tau\lambda(1 - a(1))$ where $\lambda a(1) < 1$). Because $\varepsilon_{\varphi,I} > \underline{\varepsilon}$, the pollution tax increases without bound as income rises (and moreover θ rises), and hence there must exist some I for which $\tilde{p}$ falls to 0, in which case the output of X is 0. The relative demand for X is, however, independent of income. Hence for sufficiently large I, Home must import X and export Y. The fall in pollution follows from Prop.1.

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[12] See Copeland and Taylor (1994) for a model that explores this issue.

Propositions 1, 2 and 3 contain the major implications of our model. Proposition 1 tells us that international trade has an impact on environmental quality that varies with the comparative advantage of a country. If we compare countries with similar incomes and scale, we expect to find openness associated with higher pollution in countries with a comparative advantage in the polluting good, and openness associated with lower pollution in countries with a comparative advantage in the clean good. This observation suggests that conditioning on country characteristics is important if we are to isolate trade's composition effect. Proposition 2 and 3 give us some limiting results concerning the determinants of comparative advantage. Even though comparative advantage is set by the complex interplay of income differences and relative factor abundance, these results indicate that if a country is *sufficiently rich* then the pollution haven motive for trade will eventually outweigh factor endowment considerations and this country will export the clean good in trade. Similarly, if a country is *sufficiently capital abundant* then the factor endowment basis for trade will eventually outweigh any pollution haven motive for trade and this country will export the dirty good. The theory is perhaps at its weakest here because it does not provide a simple definition of either sufficiently rich or sufficiently capital abundant. But it should be recognized that these definitions would have to be functions of the entire distribution of both factor abundance and per-capita income in the world as a whole.

3. Empirical Strategy

This section describes how we move from our theory to an estimating equation. To do so we need to discuss our data, its sources and limitations (section 3.1) and then address the links between theory and our estimating equation (section 3.2).

3.1 Data Sources and Measurement Issues

A real world pollutant useful for our purposes would: (1) be a by-product of goods production; (2) be emitted in greater quantities per unit of output in some industries than others; (3) have strong local effects; (4) be subject to regulations because of its noxious effect on the population; (5) have well known abatement technologies available for implementation; and (6), for econometric purposes have data available from a mix of developed and developing and "open" and "closed" economies. An almost perfect choice for this study is sulfur dioxide.

Sulfur dioxide is a noxious gas produced by the burning of fossil fuels. Natural sources occur from volcanoes, decaying organic matter and sea spray. Anthropogenic sources are thought to be responsible for somewhere between one-half to one-third of all emissions (UNEP (1991), Kraushaar (1988)). Emissions in developed countries accrue to a large extent from electricity generation and the smelting of non-ferrous ores; in some developing countries diesel fuel and home heating are also large contributors. SO2 is primarily emitted as either a direct or indirect product of goods production and is not strongly linked to automobile use. As a result, because energy intensive industries are also typically capital intensive, a reasonable proxy for dirty SO2 creating activities may be physical capital intensive production processes.

SO2 emissions can be controlled by altering the techniques of production in three ways. By the process of flue gas desulphurization (adding scrubbers to flue stacks), by altering the combustion process of fuels, and by a change to lower sulfur content fuels. Therefore, readily available although costly methods for the control of emissions exist and their efficacy is well established. In addition, in many countries SO2 emissions have been actively regulated for some time.

The Global Environment Monitoring System (GEMS) has been recording SO2 concentrations in major urban areas in developed and developing countries since the early 1970s. Our data set consists of 2621 observations from 293 observation sites located in 109 cities representing 44 countries spanning the years 1971-1996.[13] The GEMS network was

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[13] We have only a handful of data points (two or three observations) for some countries. Accordingly we do not draw any country specific conclusions for these countries.

set up to monitor the concentrations of several pollutants in a cross section of countries using comparable measuring devices.[14] The panel of countries includes primarily developed countries in the early years, but from 1976 to the early 1990s the United Nations Environment Programme provided funds to expand and maintain the network. The coverage of developing economies grew over time until the late 1980s. In the 1990s coverage has fallen with data only from the US for 1996. WHO (1984) reports that until the late 1970s data comparability may be limited as monitoring capabilities were being assessed, many new countries were added, and procedures were being developed to ensure validated samples. Accordingly, we investigate the sensitivity of our findings to the time period, but leave the reporting of these (largely confirming results) to Appendix C.

The GEMS data is comprised of summary statistics for several percentiles of the yearly distribution for concentrations at each site together with highest recorded values and both geometric and arithmetic means. In this study we use the log of median SO2 concentrations at a given site, for each year, as our dependent variable. We use a log transform because the distribution of yearly summary statistics for SO2 appears to be log normal (WHO (1984)). Previous work in this area by the WHO and others has argued that a log normal distribution is appropriate because temperature inversions or other special pollution episodes often lead to large values for some observations. In contrast, even weather very helpful to dissipation cannot drive the natural level of the pollutant below zero.[15]

In addition to the data on concentrations the GEMS network also classifies each site within a city as either city center, suburban or rural in land type, and we employ these land type categories in our analysis. A list of the cities involved, the years of operation of GEMS stations, and the number of observations from each city is given in Appendix A.

In moving from our theoretical model to its empirical counterpart we need to include variables to reflect scale, technique and composition effects. As well, we have to include site-specific variables to account for the density of economic activity and meteorological

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[14] The range of sophistication of monitoring techniques used in the network varies quite widely, but the various techniques have been subject to comparability tests over the years. Some stations offer continuous monitoring while others only measure at discrete intervals.

[15] For further information on the distribution of SO2 see appendix A, and our discussion of alternative transformations in appendix C.2.

conditions. Our estimations will require the use of data on real GDP per capita, capital to labor ratios, population densities, and various measures of "openness". The majority of the economic data were obtained from the Penn World Tables 5.6. The remainder was obtained from several sources. A full description of data sources and our methods for collection are provided in Appendix A together with a table of means, standard deviations, and units of measurement for the data.

3.2 Linking Theory to the Estimating Equation

To derive an estimating equation, assume measured concentrations at any observation site are a function of the country specific economic determinants of emissions, E; site-specific meteorological and density variables (V); common to world trends in abatement technology and world prices (C); and a site-specific error ε that includes other relevant, but unmeasured determinants of pollution, plus an idiosyncratic measurement error reflecting human and machine error. If we take a Taylor series approximation to this general functional form we can then write pollution concentrations at site i, city j, in country k, at time t as

$$z_{ijkt}^{E} = \beta_E E_{ijkt} + \beta_V V_{ijkt} + \beta_C C_t + \varepsilon_{ijkt} \tag{3.1}$$

where β_E, β_V and β_C are parameter vectors and E_{ijkt}, V_{ijkt} and C_t represent vectors of regressors to be explained below.

Economic Determinants

The economic determinants we include in E, follow quite directly from equation (2.22) relating differences in emissions across countries (or differences within a country over time) to differences in country characteristics and trade frictions. We reproduce (2.22) below:

$$\hat{z} = \gamma_1 \hat{S} + \gamma_2 \hat{k} - \gamma_3 \hat{I} - \gamma_4 \hat{N} - \gamma_5 \hat{\delta} + \gamma_6 \hat{p}^{w} + \gamma_7 \hat{\beta} \tag{2.22}$$

In our empirical work we measure the scale of activity at any site, S, by constructing an intensive measure of economic activity per unit area. This intensive measure is GDP per square kilometer. Lacking detailed data on "Gross City Product", we construct GDP per square kilometer for each city and each year by multiplying city population density with country GDP per person. This measure has two key benefits. First, it is measured in intensive form, as is our dependent variable. To explain *concentrations of pollution* we need a measure of scale reflecting the *concentration of economic activity* within the same geographical area. Other possible proxies for scale fail this test: GDP per person makes no allowance for cities of different size; GDP scaled by city population makes no allowance for cities of different density. Only GDP per square kilometer captures differences in the flow of economic activity per unit area across cities that vary in population size and density.

A second benefit of our measure is that it allows for heterogeneity across cities within the same country in the scale of economic activity. This within-country heterogeneity is key to disentangling the technique and scale effects.

The composition effect is captured by capital abundance, κ, as measured by a nation's capital to labor ratio. We implicitly assume that this ratio is the same for all cities within a country. In our estimations we will include both a country's capital to labor ratio and its square. This non-linearity is appealing because theory suggests capital accumulation should have a diminishing effect at the margin.

We proxy our technique effect by a moving average of lagged income, I. Because we believe the transmission of income gains into policy is both slow and reflects long run averages, we use as our proxy for income a (one period lagged) three year moving average of GDP per capita. We have also allowed the technique effect to have a diminishing impact at the margin by entering both the level and the square of income per capita in all of our regressions.

Population size, N, appears in (2.22) because the Samuelson rule sums marginal damage over all individuals exposed to a unit of pollution. Air pollution standards are in most countries uniform throughout the country with the actual level of the standard either set by, or heavily influenced by, national governments. Since policy is nation wide, our theory would indicate that the relevant regressor arising from the Samuelson rule would be some average number of exposed individuals taken from a mix of metropolitan and non-metropolitan areas in the country. Exposure would also have to reflect country specific disbursement potential and weather patterns. Since we have very little confidence in our ability to construct a suitable proxy, we treat this factor as an unobservable component in our error term.

Changes in tastes or knowledge concerning pollution, plus changes in world prices are treated as common-to-world trends and are discussed subsequently in the section on common-to-world determinants.

Finally our theory ties trade frictions β to pollution concentrations, but the sign of this composition effect depends on a country's comparative advantage. Comparative advantage is in turn a function of a country's income per capita and its capital abundance. To capture this feature in our empirical work we proceed as follows. First, we need a measure to reflect the extent to which international trade affects the domestic economy. We adopt for this purpose a country's trade intensity ratio: the ratio of exports plus imports to GDP. This proxy accords well with our theory because a movement of β towards 1 raises the ratio of exports plus imports to GDP for any country.

Second, we then need to condition this impact on country characteristics. To condition the impact of openness on country characteristics we interact the trade intensity measure with our model's predicted determinants of comparative advantage. Within our framework the most important country characteristics determining trade patterns are a country's capital to labor ratio and its income per capita. Moreover, because comparative advantage is a relative concept, we express our measures of country characteristics relative to their corresponding world averages.[16] This procedure allows us to condition the predicted environmental impact of further openness on our theoretical determinants of comparative advantage.

Finally, we need to somehow account for the two possible motives for trade when we introduce our interaction terms with country characteristics. In general the trade-off between the factor endowment basis for trade and the pollution haven motive is exceedingly complex and not amenable to simple formulation.[17] Rather than imposing specific functional

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[16] See appendix A for details.

[17] Without imposing severe restrictions on the relative factor intensities in the two industries, elasticities of substitution in production, and elasticities of marginal damage from pollution it is not possible to state precisely how these two potentially offsetting characteristics interact to determine a nation's comparative advantage.

forms that arise from some tractable special cases of our model, we instead rely on the results presented in Proposition 2 and 3. Because our theory does not tell us at what point further increases in the capital to labor ratio raise pollution (via the composition effect) or when increases in per capita income finally lower pollution (via the composition effect), we adopt a flexible approach to estimation. We interact a quadratic in a country's (relative) characteristics with its trade intensity ratio.

We then expect our interacted quadratic in relative capital to labor to imply a positive impact of further openness for high capital to labor ratios but a negative effect for lower levels. Proposition 2 shows that regardless of a country's other characteristics if its capital to labor ratio is sufficiently high relative to those of its trading partners then it must export good X.[18] Alternatively, if its capital to labor ratio is relatively low then it must import good X. This partial result reflects the factor endowment hypothesis.

Similarly we expect that our quadratic in relative income per capita to imply a negative impact of further openness on concentrations for high incomes but a positive effect for lower incomes. Proposition 3 indicates that regardless of other country characteristics, if a country's income per capita is sufficiently high it must import good X. Alternatively if its income per capita is relatively low, it must export good X. This partial result reflects the pollution haven hypothesis.

Site-specific Determinants

Since our data are observations of ground level SO2 concentrations at sites in various participating cities around the world it is apparent that site-specific weather and topographical conditions may have a large bearing on concentration levels for any given level of emissions. Unmeasured topographical features are captured in some of our estimations through site-specific fixed and random effects. In earlier research, measured site-specific influences such as proximity to oceans or deserts have sometimes proven useful[19]. Our

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[18] Strictly speaking the proposition says that if a country's capital to labor ratio exceeds some threshold level taking income I and world price p as given then the composition effect of trade must be positive. In fact world prices are determined by the rest of world's abundance in capital and hence our relative statement in the text.

[19] See for example Grossman and Krueger (1993).

experience with these variables has been that they are rarely significant in determining concentrations. In addition to site-specific fixed effects we also employ city-specific weather variables to capture differences across cities in their natural cleansing abilities and in seasonal influences on emissions. While weather variables are unlikely to be strongly correlated with our economic variables their inclusion may help us obtain more accurate estimates. To capture seasonal influences on the demand for fuels and hence emissions of SO2 we include the average monthly temperature from each site. As well we have included the variation in precipitation at the site as well to proxy for the ability of precipitation to wash out concentrations. If precipitation is largely concentrated in one season then its ability to wash out concentrations over the year is reduced. Seasonal influences have been found to be important in similar studies (See for example WHO (1984)).

Common-to-World Determinants, Error Components and Excluded Variables

We assume our error term ε_{ijkt} is composed of three elements. First, a common-to-world but time varying component λ_t reflecting trends in the public's awareness of environmental problems, in abatement technology, and in world prices. We capture these common-to-world components via a linear time trend.[20] Second, we include time invariant site components θ_{ijk} to reflect unmeasured meteorological or topographical features of a site as well as any time invariant country-specific effects such as government or country type. And finally we include an idiosyncratic component ν_{ijkt} reflecting both human and machine measurement error at the site. Most of these assumptions are not controversial, although the issue of government type deserves some discussion.

In developing our model we allowed pollution policy to be flexible and responsive to changes in the economy. In contrast, we took the existing level of trade frictions β as exogenous. Since trade frictions undoubtedly contain a component reflecting trade policy we have in fact taken this part of policy as exogenous. This assumption may be problematic if pollution and trade policies are correlated because political economy considerations, income levels, and other factors jointly determine them. Consider for example government type.

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[20] In appendix C we show that our results are not affected by allowing for a full set of unrestricted time dummies as well.

Suppose our sample of countries was divided into two types: democracies and communist countries. Suppose democracies are both relatively open and fairly clean, while communist countries are relatively closed to trade and very dirty. As a result, if we ignore the correlation of trade and environmental policy induced by political systems, our trade intensity measure may be correlated with our equation's error term. All else equal, open economies will appear cleaner because they are open rather than because they are democracies.

In this simple case, the problem is not difficult to remedy and we do so by allowing for a communist dummy in our estimations.[21] In other cases such a simple fix is not available. Many of the candidate measures of trade frictions or "openness" may be contaminated by other more subtle country characteristics that jointly determine trade and environmental policy. For example, the trade intensity variable we employ reflects country type considerations such as proximity to markets, geographic size and natural resource endowments and in general tends to be highest for small countries within close proximity to their trading partners. Because our pollutant under study is well known to have serious transboundary effects, there may be a correlation between countries with large measured openness and SO2 regulation.[22] The openness measure developed by Sachs and Warner (1995) and measures of the black-market exchange-rate premium also suffer from similar problems.

Panel-data methods offer different ways to deal with the possibility of country-specific and/or site-specific excluded variables. When such effects are viewed simply as parametric shifts of our regression function, a suitable estimation approach is the least-squares dummy-variable (i.e., fixed-effects) estimator that treats these effects as constants. This approach is appropriate when the model is viewed as applying only to the countries or observation sites in the sample but not to additional ones outside the sample. If, however, the model is viewed as a random draw of countries or observation sites from a larger population, it is appropriate to use a random-effects estimator to capture the level effect

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[21] Further, in some estimations we interact this dummy with our income per capita terms to test the hypothesis that communist governments care little about their public's demand for a cleaner environment.

[22] For example, many countries in Europe are very open by our measure while the U.S. is not. At the same time, European countries are much more sensitive to, and aware of, the problems caused by acid rain than is the U.S. Therefore, there may be a cross-sectional negative correlation between SO2 concentrations and openness as measured in our data set. Once again we must be careful about using the cross-sectional variation in our data set. We do not want to attribute to openness or trade what is due to geography.

through a random variable. Because this estimator treats the level effects as uncorrelated with the other regressors, it may suffer from inconsistency due to omitted variables. By comparison, the fixed-effects estimator does not suffer from this inconsistency problem, but it focuses exclusively on the variation over time in our data. Acknowledging the strengths and weaknesses of both types of estimators, our strategy is to estimate both fixed and random effects versions of our model whenever possible. We also report results from the Hausman test comparing these two methods.[23] Occasionally we are forced to rely on the random effects implementation alone because some of our regressors would not be identified in a fixed effects estimation. Both of these methods have been widely used in the literature.[24]

The Estimation Equation

Combining the economic, site-specific, and common-to-world components we obtain:

$$\begin{aligned} z_{ijkt} = {} & \beta_0 + \beta_1 GDP_{jkt} + \beta_2 KL_{kt} + \beta_3 (KL_{kt})^2 + \beta_4 I_{kt} + \beta_5 (I_{kt})^2 + \\ & \beta_6 R_{ijk} + \beta_7 B_{ijk} + \beta_8 M_{jkt}^T + \beta_9 M_{jkt}^P + \beta_{10} O_{kt} + \beta_{11} O_{kt}\, RKL_{kt} + \\ & \beta_{12} O_{kt}\, (RKL_{kt})^2 + \beta_{13} O_{kt}\, RI_{kt} + \beta_{14} O_{kt}\, (RI_{kt})^2 + \varepsilon_{ijkt} \qquad (3.2) \end{aligned}$$

where GDP_{jkt} is measured by real GDP/km^2, KL_{kt} is measured by the capital to labor ratio, I_{kt} is one period lagged three year moving average of GDP per capita, R_{ijk} is a dummy indicating site ijk is in a rural location, B_{ijk} is a dummy indicating site ijk is in a suburban location, M_{jkt}^T is average temperature in city j at time t, M_{jkt}^P is the variation in precipitation in city j at time t, O_{kt} is measured by the ratio of exports and imports to GDP, $O_{kt}\, RKL_{kt}$ and $O_{kt}\, (RKL_{kt})^2$ are interactions of openness with country k's relative capital to labor ratio and

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[23] Moulton (1987) cautions against misinterpreting the Hausman test. The fixed-effects estimator is very sensitive to errors-in-variables. Rejection of the Hausman test could be due to either correlation between the regressors and the group effects, ***or*** bias from errors-in-variables intensified under the fixed-effects model.

[24] See for example Grossman and Krueger (1993, 1995), Seldon and Song (1995), Shafik (1994), etc.

its square, and $O_{kt}\ RI_{kt}^{C}$ and $O_{kt}\ (RI_{kt})^2$ are interactions of openness with country k's income per capita and its square. In addition to these determinants we include a dummy for communist countries in all of our estimations.

4. Empirical Results

4.1 Empirical Strategy

Our empirical strategy has four steps. We first estimate (3.2) excluding the terms involving openness to determine whether our simple model specification capturing scale, composition and technique effects is useful in explaining pollution concentration levels around the world. We then take a second step by adding several measures of "openness" to our basic model and noting the consequences. Our purpose here is to investigate whether a simple and definitive relationship exists between openness to international markets and pollution concentrations (after controlling for differences across countries in scale, factor endowments, etc.) In our third step, we include our openness interactions to allow trade's effect to differ across countries. Our theory would suggest that conditioning the impact of further openness on country characteristics is the key to determining how trade affects the pollution intensity of national output. In our fourth and final step we combine our scale, technique and trade intensity elasticities to provide a preliminary assessment of how trade affects SO2 concentrations.

Scale, Composition and Technique Effects

Table 1 presents initial estimates from our random and fixed effect implementation of (3.2). There are three important properties shown in the table.

First, there is a comforting consistency across the regressions in both the size and sign of the estimated coefficients. Second, at conventional levels of significance the vast majority of all coefficients are statistically different from zero. Third, the results are almost universally in line with the theory detailed in section 2.

TABLE 1: THE DETERMINANTS OF SO_2 CONCENTRATION

Variable	Fixed Effects		Random Effects	
Intercept	-4.27278^{**}	(8.80)	-3.57378^{**}	(12.26)
GDP/km^2	0.04659^{**}	(4.41)	0.05342^{**}	(8.62)
Capital abundance (K/L)	0.05061^{**}	(3.10)	0.03176^{**}	(2.63)
$(K/L)^2$	-0.00078^{**}	(4.51)	-0.00054^{**}	(3.98)
Lagged p.c. income (I)	-0.11068^{**}	(2.84)	-0.13462^{**}	(4.60)
I^2	0.00286^{**}	(2.98)	0.00316^{**}	(3.86)
Communist Country			0.34283	(1.65)
Suburban			-0.48528^{**}	(2.69)
Rural			-0.73596	(1.90)
Average Temperature	-0.04400	(1.80)	-0.06034^{**}	(5.88)
Precipitation Variation	6.13769	(1.45)	3.73900	(0.96)
Time Trend	-0.03491^{**}	(6.76)	-0.03501^{**}	(8.63)
Observations / Groups	2621	293	2621	293
R^2 (overall)	0.204		0.329	
Hausman Test	$\chi^2_8 = 21.38$			

Note: T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Dependent variable is the log of the median of SO_2 concentrations at each observation site.

TABLE 2: ISOLATING TRADE'S EFFECT: A FIRST STEP

	Openness (X+M) /GDP	Black Market Premium	Avg. Tariff [%]	Avg. Quota [%]	Sachs& Warner Dummy
Estimate	-0.00239	0.02606	0.00088	0.00594	0.03934
t-Stat.	(1.819)	(1.496)	(0.349)	(1.917)	(0.454)
Obsv.	2621	2621	2369	2298	2621
Groups	293	293	270	263	293
R^2	0.326	0.324	0.354	0.364	0.324

Note: The results shown were obtained through a random-effects estimation. T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Dependent variable is the log of the median of SO_2 concentrations at each observation site. Note that the black market premium, average tariff and quota coverage variables measure the *inverse* of openness; their sign has thus to be reversed to interpret the direction of the estimates as an increase in openness.

Consider our core variables representing scale, composition and technique effects. In both columns of table 1 we find a positive relationship between the scale of economic activity as measured by GDP/km^2 and concentrations. Similarly, both columns report that an increase in the capital labor ratio raises emissions - consistent with a positive composition effect - albeit increases in this ratio have a diminishing impact much as we may expect. This diminishing effect probably reflects a lower average pollution intensity of capital equipment in high-income countries. Our theory predicts that high-income countries have tighter standards in place, and this in turn implies the pollution consequences of capital accumulation should fall as development proceeds. Finally, the income per capita terms indicate a strong and significantly negative relationship between per capita income levels and concentrations. We again find a diminishing effect but it is less pronounced than that for the capital to labor ratio.[25]

From table 1 it also appears that our strategy for identifying the separate, but related, impacts of changes in scale and technique is successful. Recall that since scale is measured in the intensive form GDP/km^2 there is within-country heterogeneity in the scale variable for most countries. If, as we assume, pollution policy is determined by average income per capita in a country, then variation in the scale variable across cities within the same country can be used to separate the influence of scale from that of technique. Therefore the recognition that scale should be measured in intensive form together with a theoretical restriction linking policy to national income allows us to disentangle these two effects in our data.

In addition to these observations table 1 also reports that it may be important to distinguish between communist and non-communist countries. This would appear to support our concerns to distinguish carefully across countries according to the type of political system. If we investigate further and interact the communist dummy with our income terms reflecting the technique effect we find that pollution concentrations in communist countries are much less responsive to increases in real income. This result is consistent with our theory as it implies that $\varepsilon_{T,\tau}$ is must smaller for communist countries. In the fixed effects case, the elasticity of concentrations to an increase in per capita income in communist

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[25] We have estimated the turning points for both quadratics and their confidence intervals. These estimates and their confidence intervals can vary quite widely according to the specification. Our robust finding is that of a diminishing effect at the margin. The turning points may or may not fall outside of the sample range.

countries has a point estimate of 0.594 but the 95% confidence interval includes zero and is given by (-0.139,1.326). And hence we cannot reject the hypothesis of no technique effect in communist countries! In the random effects case, the point estimate is -0.587 with a 95% confidence interval of (-1.062,-0.111). We have excluded the communist-income interaction terms from table 1 to avoid clutter, but include them in all subsequent regressions.

It also appears that weather has a significant affect on concentrations. We find an increase in average temperature reduces concentrations as we may expect, and an increase in the concentration of yearly precipitation raises concentrations. Finally, the estimates indicate that locations in less dense areas, either suburban or rural locations, experience less pollution than locations at city center (our excluded category).

Isolating Trade's Effect

We now investigate several relatively simple hypotheses regarding the effect of international trade on pollution concentrations by adding various measures of "openness" to the random effect implementation of our model. We are forced to limit ourselves to a random effect implementation because many of the candidate measures of openness are not identified in a fixed effect implementation. The estimated coefficient for the openness variable introduced in each regression is reported in table 2 below. All other estimates are suppressed because the inclusion of the additional variable had very little if any impact on the other estimates as reported in table 1.[26]

The new variables are: (1) the ratio of exports plus imports to GDP (i.e. trade intensity); (2) a measure of the black market premium in foreign exchange markets over the 1970s and 1980s (BMP); (3) the average level of tariffs on imports over 1985-88 (Tariffs); (4) the percent of imports affected by a quota over 1985-1988 (Quotas); and (5), an indicator variable created by Sachs and Warner (1995) reflecting a country's policy stance toward trade (Sachs). All of these measures except for the trade intensity measure were taken from Sachs and Warner (1995, p65-66).

In their study of the NAFTA, Grossman and Krueger (1993) employ the trade intensity measure and report a significant and negative relationship between concentrations

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[26] See appendix B for the complete set of estimates.

and trade intensity. We establish a similar result although the variable is not significant at conventional levels. We note that the black market premium enters positively, suggesting that moving away from world markets and restricting convertibility may be correlated with an increase in pollution concentrations, although again this relationship is not significant at conventional levels. There is little to report regarding the relationship between concentrations and tariff levels, but there appears to be a positive relationship between quota coverage and concentrations. The Sachs and Warner measure in column 5 appears to add little as well.

Overall the estimates given in table 2 offer very little evidence of a strong relationship between openness, however measured, and resulting pollution concentrations. It is possible to pick and choose carefully from the table to craft a story where openness to international markets is good for the environment. Neglecting statistical significance, we could note that an increase in openness lowers pollution, while a rise in quota coverage or a movement away from international markets and currency convertibility raises pollution. This reading of table 2 is, however, very selective.

Our reading of table 2 is far less complex: the lack of any significant relationship between concentrations and openness is exactly what we might expect to find. After controlling for other differences across countries, the impact of further openness on pollution should, in theory, only reflect the induced composition effect of trade. But the sign of this trade-created composition effect should vary with country characteristics. If we fail to condition on country characteristics, then we are at best measuring an average, unconditional, effect of openness. This unconditional response may be positive or negative and will depend on the characteristics of countries in our sample.

4.2. A Second Step: Conditioning on Country Characteristics

We now present estimates from our complete model allowing for the interaction of country characteristics with a measure of openness. We report only interactions with the trade intensity measure of openness because other candidate measures have either very little time series variation or were eliminated because of insufficient data. We report the results for our second step procedure for finding trade's effect in table 3.

Table 3: Isolating Trade’s Effect: A Second Step

Variable	Fixed Effects		Random Effects	
Intercept	-3.66165^{**}	(6.71)	-3.05851^{**}	(9.39)
GDP/km^2	0.04263^{**}	(3.64)	0.05418^{**}	(8.08)
Capital abundance (K/L)	0.11915^{**}	(6.04)	0.09194^{**}	(5.83)
$(K/L)^2$	-0.00149^{**}	(6.76)	-0.00123^{**}	(6.92)
Lagged p.c. income (I)	-0.31075^{**}	(5.50)	-0.29750^{**}	(7.72)
I^2	0.00740^{**}	(6.10)	0.00687^{**}	(6.74)
Communist Country			-0.45554	(1.16)
C.C. $\times$ I	1.15287^{**}	(4.48)	0.30231	(1.85)
C.C. $\times$ I^2	-0.08355^{**}	(4.00)	-0.02066	(1.38)
θ =(X+M)/GDP in %	-0.02293^{**}	(3.34)	-0.01078^{*}	(2.25)
$\theta\times$ relative (K/L)	-0.03054^{**}	(5.69)	-0.02290^{**}	(6.12)
$\theta\times$ relative $(K/L)^2$	0.00592^{**}	(5.12)	0.00427^{**}	(5.70)
$\theta\times$ relative income	0.03428^{**}	(5.38)	0.02247^{**}	(4.95)
$\theta\times$ relative income sq.	-0.00523^{**}	(3.72)	-0.00330^{**}	(3.19)
Suburban			-0.43767^{*}	(2.33)
Rural			-0.67739	(1.74)
Average Temperature	-0.05924^{*}	(2.42)	-0.06161^{**}	(5.87)
Precipitation Variation	7.96498	(1.89)	3.98493	(1.03)
Time Trend	-0.03838^{**}	(6.85)	-0.03400^{**}	(7.70)
Observations / Groups	2621	293	2621	293
R^2 (overall)	0.137		0.343	
Hausman Test	$\chi^2_{15} = 62.79$			

Note: T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Dependent variable is the log of the median of SO_2 concentrations at each observation site.

Table 4: Scale, Composition, Technique, & Trade Elasticities

Elasticity	Estim.	Std.Err.	95%-Conf. Iv.
Fixed Effects Regression			
Scale	0.193	0.053	0.089 / 0.297
Composition	1.135	0.301	0.546 / 1.724
Technique	-1.611	0.366	-2.328 / -0.894
Trade Intensity	-0.869	0.149	-1.161 / -0.576
Random Effects Regression			
Scale	0.245	0.030	0.186 / 0.305
Composition	0.783	0.230	0.332 / 1.233
Technique	-1.580	0.222	-2.015 / -1.146
Trade Intensity	-0.533	0.093	-0.715 / -0.351

Note: All elasticities are evaluated at sample means.

There are several features of note in the table. First, adding the openness interactions has not undermined the model's basic predictions regarding scale, technique and composition effects. In particular, the sign of our basic regressors is maintained and in most cases the significance levels are enhanced by the inclusion of the openness interactions.

Second, the inclusion of country characteristics appears to have made a large difference to the impact openness has on pollution. The coefficient on our measure of openness is now highly significant whereas in table 2 it was not significant at conventional levels. Its magnitude is now approximately ten times its former size. The interaction terms with country characteristics are also highly significant.

Third, the sign pattern of the interaction terms is as expected from theory. The linear interaction term on openness and (relative) income per capita is positive in both columns and the quadratic term is always negative. Consequently if a country has a relatively low level of income per capita relative to the rest of the world, then – all else equal - the impact of further openness must be to make this country dirtier. Relatively rich countries would be made cleaner with trade. These results may reflect the ceteris paribus pollution haven hypothesis where relative income differences alone determine the composition effect of trade. Similarly, the linear interaction term on (relative) capital intensity is always negative and the quadratic term always positive. Therefore, if a country has a sufficiently high capital to labor ratio relative to the rest of the world, then the impact of further openness must be to make this country dirtier. Capital-scarce countries would be made cleaner with trade. This sign pattern may reflect the ceteris paribus factor-endowment hypothesis where factor abundance differences alone determine the composition effect of trade.

Together these results indicate that scale, technique and composition effects are still at work determining pollution concentrations but open economy considerations also matter. But while the sign and statistical significance of the estimates in table 3 are supportive of our approach it is important to investigate whether the magnitude of the coefficient estimates are in some sense plausible.

Scale, Composition and Technique Elasticities

There are several ways to evaluate these results. One method is to examine whether the implied elasticity estimates for scale (GDP/km^2), technique (income per capita), composition (capital to labor ratio), and trade intensity (exports plus imports divided by GDP) lead to implausible conclusions regarding income growth or technological progress. In table 4 below we present the elasticities implied by our estimates in table 3. All elasticities are evaluated at the sample means and therefore can be interpreted as those applying to an "average country" in our sample. In calculating the technique and composition elasticities we have assumed that our "average" country's relative position in the world remains constant when it undergoes either income growth or capital accumulation.

The results in table 4 are largely supportive of our theory. The estimated elasticities are not implausibly high, and all elasticity estimates are significantly different from zero. Moreover the signs for the scale, technique and composition elasticities are as predicted by theory. To investigate the plausibility of these estimates further note that neutral technological progress of 1% would raise GDP and GDP per person by 1%. Therefore, neutral technological progress creates a positive scale effect on concentrations, but according to our estimates this scale effect is more than offset by a negative technique effect.[27] Therefore our estimates indicate that increases in economic activity driven by neutral technological progress lowers concentrations.

Alternatively, if we consider an increase in GDP fueled entirely by capital accumulation the picture is far less favorable to the environment. Our estimates indicate that a 1% increase in the capital to labor ratio raises concentrations by about 1% all else equal. However an increase in the capital to labor ratio will have accompanying impacts on the scale of economic activity and on real incomes. If we make a back-of-the-envelope calculation by taking capital's share in the value of domestic output at 1/3, then capital accumulation leading to a 1% increase in the capital to labor ratio creates a 1/3 percentage point increase in GDP per capita and GDP/km^2. Applying the estimates from table 4 we find that the induced technique effect is approximately -.5 and the induced scale effect is perhaps .08. Adding the direct composition effect to these estimates suggests that economic growth fueled entirely by capital accumulation raises pollution concentrations.

While these two exercises are not tests of our theory, the results are reassuringly close to what we may have expected ex ante. More speculatively, these last two thought

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[27] In the fixed effects case the point estimate for such an experiment is -1.45 with a 95% confidence interval of (-2.1, -.76). The random effects case tells a similar story with a point estimate of -1.36 with a confidence interval of (-1.78, -.95).

experiments may also provide a possible explanation for the Kuznets curve that many authors have found between pollution and per capita income. If economic growth is driven primarily by capital accumulation in the early stages of development, and primarily by technological progress in later years, then our results indicate that pollution concentrations may at first rise and then fall with increases in income per capita.

Trade Intensity Elasticity

Next consider the trade intensity elasticity. The trade intensity elasticity measures the predicted change in concentrations for a 1% change in the ratio of exports plus imports to GDP. This measure indicates that a 1% change in the share of trade in GDP should reduce concentrations by .53% in the random effects model and .86% in the fixed effects model. These seem rather large in isolation, but the estimates from table 3 also indicate that technological progress in abatement technology or changing knowledge and attitudes toward pollution appear to be driving concentrations down by 3-4% per year.

Note our trade intensity estimate (evaluated at the mean of our sample) is negative and significantly different from zero in both formulations. This is a somewhat surprising result because it indicates that trade has an overall negative composition effect rather than a close to zero effect we may have expected. Proposition 1 indicates that the sign of the trade intensity elasticity should reflect a country's comparative advantage in clean versus dirty goods. Therefore it is not plausible that all countries in the world have a negative composition effect. Although we have only a sample of countries it seems reasonable to expect both positive and negative elasticities.

As a check on our theory we calculated each country's trade elasticity. We find that the country specific elasticity estimates are both positive and negative.[28] About 1/3 of the countries have trade elasticities indistinguishable from zero. We find some positive elasticity estimates, but the majority of elasticities in our sample are negative and statistically different from zero. These findings are roughly consistent with our theory, because our theory only predicts that there should be a distribution of these elasticities around zero.

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[28] See appendix table B.2.

FIGURE 1:
Country-specific Openness Elasticities vs. Relative Income

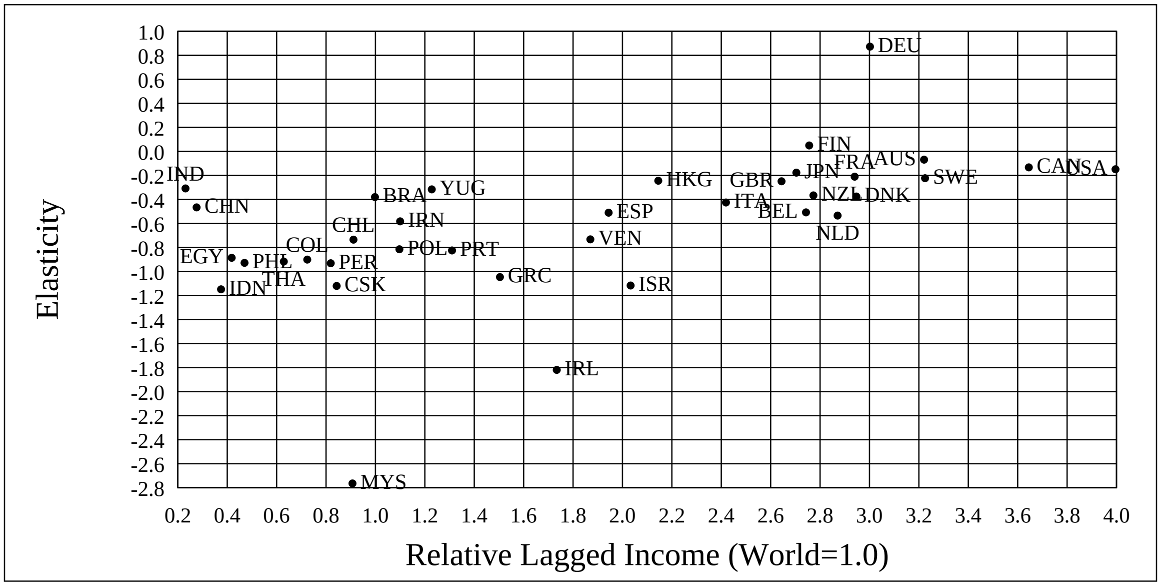
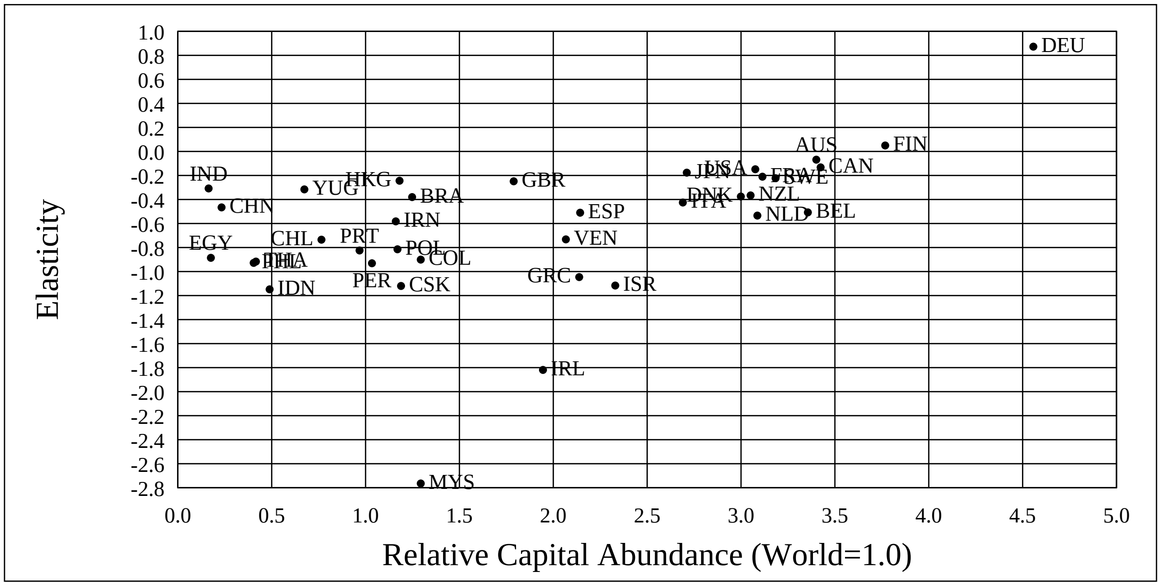


FIGURE 2:
Country-specific Openness Elasticities vs. Relative Capital Abundance



Note: The elasticities shown in the above diagrams correspond to the random-effects regression presented in table 3, evaluated at corresponding sample means. Countries with less than five observations in the data set were excluded from the above diagrams.

Finally we may ask what country characteristics are tied with a trade elasticity that is negative or one that is positive. If the compositional effects of trade were primarily driven by the simple pollution haven hypothesis we would expect a strong negative correlation between relative income and the magnitude of the trade elasticity. In fact as shown in Figure 1, there is no such relationship between the size of a country's trade elasticity and its relative income level.

Similarly, if the compositional effects of trade were primarily driven by the simplest factor endowment hypothesis we would expect a strongly positive relationship between relative capital abundance and the sign of a country's trade elasticity. In fact as shown in Figure 2, there is little apparent relationship between the strength of a country's trade elasticity and its relative capital abundance.

The explanation for these finding is simple: low-income countries typically have both low income per capita and low capital to labor ratios. The pollution haven hypothesis suggests that a low-income economy should be made dirtier by trade, but if pollution intensive industries are also capital intensive then whatever benefits accrue from lax pollution regulation could be largely undone by the relatively higher price of capital in this capital scarce country. As a result, further openness to trade will have a very small effect on the pollution intensity of output for low-income countries. Similarly, high-income countries have both high income and high capital to labor ratios. The former argues in favor of trade lowering the pollution intensity of output, while the latter argues in favor of trade raising it. It is not that the (ceterus paribus) pollution haven hypothesis is wrong, or that the (ceterus paribus) factor endowment driven basis for trade is absent. Rather it is that given the relationship between income per capita and capital to labor ratios (summarized for example by the one-sector neoclassical growth model) these two partial theories work against each other. Consequently, the potentially very large composition effects predicted by either theory turn out to be relatively small in practice.

4.3 The Last Step: Putting it all Together

We argued previously (in section 2.3) that because we could not quantify the impact of trade liberalization on either GDP or GDP per person we could not identify the impact of trade liberalization on pollution through either the scale or the technique effect. Our empirical strategy could at best provide an estimate of the composition effect created by trade. We would now like to suggest that this admission of defeat was in fact a strategic retreat from the question posed in our title - not an outright surrender. Our estimates in table 4 indicate that a change in GDP that creates both a scale and technique effect (but leave a country's K/L unchanged) will lower pollution. One possible cause for such a change is neutral technological progress. Trade liberalization is another: taking factor endowments as fixed, a lowering of transport costs or trade barriers raises the value of domestic output and real income for a small open economy. The value of output and the value of income rise by the same percentage and this creates both scale and technique effects.

Our estimates indicate that the net effect of this trade-induced increase in output and income will be a fall in concentrations. For example, if we use the estimates from the fixed-effects regression from table 4, the scale elasticity for an average country is .193 while the technique elasticity is –1.611. Taken together, they imply a net effect of -1.418 with a 95% confidence interval of (-2.110, -0.726). The composition effect of trade for our average country is also negative. It is apparent then that for an average country in our sample, the full impact of further openness to international trade - through scale, technique and composition effects - will be a reduction in SO2 concentrations!

How large a reduction any one country reaps from a reduction in trade frictions will of course depend on country characteristics, the impact further trade has on domestic income and output, and how the ongoing process of globalization is affecting country characteristics elsewhere in the world. Since countries will differ somewhat in their particular scale, technique and trade intensity elasticities, some may indeed be made dirtier from a reduction in trade frictions, but we expect that trade's effect – whether positive or negative – will be small. After all the estimated impact of even a large trade liberalization on GDP is small, and when this small increase in GDP is then filtered through our estimated scale and technique elasticities the net effect is likely to be smaller still. While in theory, trade's impact on the pollution intensity of output can be large, in practice our estimates suggest a much more muted response.

These conclusions rely however on our assumption that factor endowments and technology remain fixed when trade frictions fall. If further trade spurs capital accumulation or if trade brings knowledge spillovers and hastens technological progress then other calculations must come into play. Whether these trade-induced changes bring about a net improvement in the environment will depend quite delicately on their estimated size since our estimates indicate that they have opposing effects on pollution concentrations. There is a burgeoning empirical literature linking openness to growth and technology adoption and we have nothing new to add here. But clearly our estimates together with input from these other sources might provide another method for assessing trade's full impact.

While the balance of our evidence suggests that freer trade is more likely to be good rather than bad for the environment, this conclusion is subject to several provisos. Our work has several strong maintained assumptions that may be false. As well, our data is not perfect, and it is important to emphasize that the pollutant we study - sulfur dioxide - is but one of many pollutants that may be affected by trade. Clearly much more work could and should be done along these lines. And while we are reasonably confident in our analysis some readers may want further analysis. In order to meet these demands we present a series of sensitivity tests in Appendix B. In this appendix we investigate whether our findings are robust to: changes in the dependent variable (mean, median, 95%, etc.); other transformations of the dependent variable (Box-Cox, linear); the inclusion of unrestricted time dummies; the inclusion of resource endowments and the real price of energy; changes in the time period of the analysis; and changes in the estimation procedure to allow for the simultaneous determination of both income and pollution levels. Overall the results in Appendix B are surprisingly similar to those presented in the text. The main features of our analysis remain intact: the technique effect remains surprisingly strong in relation to the scale effect, and our trade intensity interactions retain their sign and significance levels.

5. Conclusion

This paper sets out a theory of how openness to trading opportunities affects pollution concentrations. We started with a theoretical specification that gave pride of place to scale, technique and composition effects and then showed how this theoretical decomposition is useful in thinking about the relationship between openness to international markets and the environment. In our empirical section we adopted a specification directly linked to our earlier theory. We then estimated this specification paying special attention to the potentially confounding influences introduced by the panel structure of our data set. Our results consistently indicate that scale, technique and composition effects are not just theoretical constructs with no empirical counterparts. Rather these theoretical constructs can be identified and their magnitude measured. Moreover, once measured they can play a useful role in determining the likely environmental consequences of technological progress, capital accumulation or increased trade. These estimates may also be useful in aggregate CGE modeling of the effects of various free trade agreements and other trade reforms [see for example, Ferrantino et al.,1996].

Overall the results indicate that increases in a country's exposure to international markets creates small but measurable changes in pollution concentrations by altering the pollution intensity of national output. While our estimates indicate that greater trade intensity creates only relatively small changes in pollution via the composition effect, economic theory and numerous empirical studies demonstrate that trade also raises the value of national output and income. These associated increases in output and incomes will then impact on pollution concentrations via our estimated scale and technique effects. Our estimates of the scale and technique elasticities indicate that if openness to international markets raises both output and income by 1%, pollution concentrations fall by approximately 1%. Putting this calculation together with our earlier evidence on composition effects yields a somewhat surprising conclusion: freer trade is good for the environment.

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Appendix A

Description of The Data Set

A.1 The Dependent Variable

The dependent variable in our study is the concentration of sulphur dioxide at observation sites in major cities around the world as obtained through the GEMS/AIR data set supplied by the World Health Organization. Measurements are carried out using comparable methods. Each observation station reports annual summary statistics of SO_2 concentrations such as the median, the arithmetic and geometric mean, as well as 90th and 95th percentiles. The raw data supplied by the WHO were processed by the United States Environmental Protection Agency (EPA) and are disseminated to the public through the EPA's web site. We have obtained a more comprehensive version of what is released directly from the EPA.

We have chosen to use a logarithmic transformation of the median SO_2 concentration as our dependent variable. Figure A.1 shows that the distribution of concentrations is highly-skewed towards zero when viewed on a linear scale. In this diagram, the horizontal axis shows ranges of median SO_2 concentrations in parts per million per cubic metre [ppm/m3]. As was pointed out in the WHO (1984) report about the GEMS/AIR project, concentrations are more suitably described by a log-normal distribution. This is apparent in figure A.2 where the horizontal axis is logarithmic. The large number of observations in the bin at the very left of the diagram can be explained by the measurement threshold of the measurement devices; they cannot measure arbitrarily low concentrations. There is also an ambient level of SO_2 in the air that has natural causes.

The composition of the data set by contributor countries is shown in the pie diagram of figure A.3. A large share of observations were from the United States, due to this country's extensive network of air quality measurement stations. Other large contributor countries were China, Canada, and Japan. All in all, our analysis is based on over 2,600 observations from 293 observation stations in 109 cities around the world; these cities are located in 44 countries. Figure A.4 reveals the time period during which individual countries participated in the GEMS/AIR project. The countries are ranked by length of participation. Numerous countries provide more than fifteen years of observations, among them the United States, Canada, Germany, and Japan. In addition, table A.1 lists the cities in which the observation stations were located along with the number of stations in each city and the minimum and maximum concentrations measured at any of the stations in a given city.

A.2 Data Sets

The data set was constructed from a variety of sources that are described in detail below and are summarized in the following diagram:

`GEMS/AIR` The primary source for our data is the AIRS Executive International database that contains information about ambient air pollution in nations that voluntarily provide data to the GEMS/AIR Programme sponsored by the United Nations World

Figure A.1: Distribution of the Dependent Variable (linear scale)

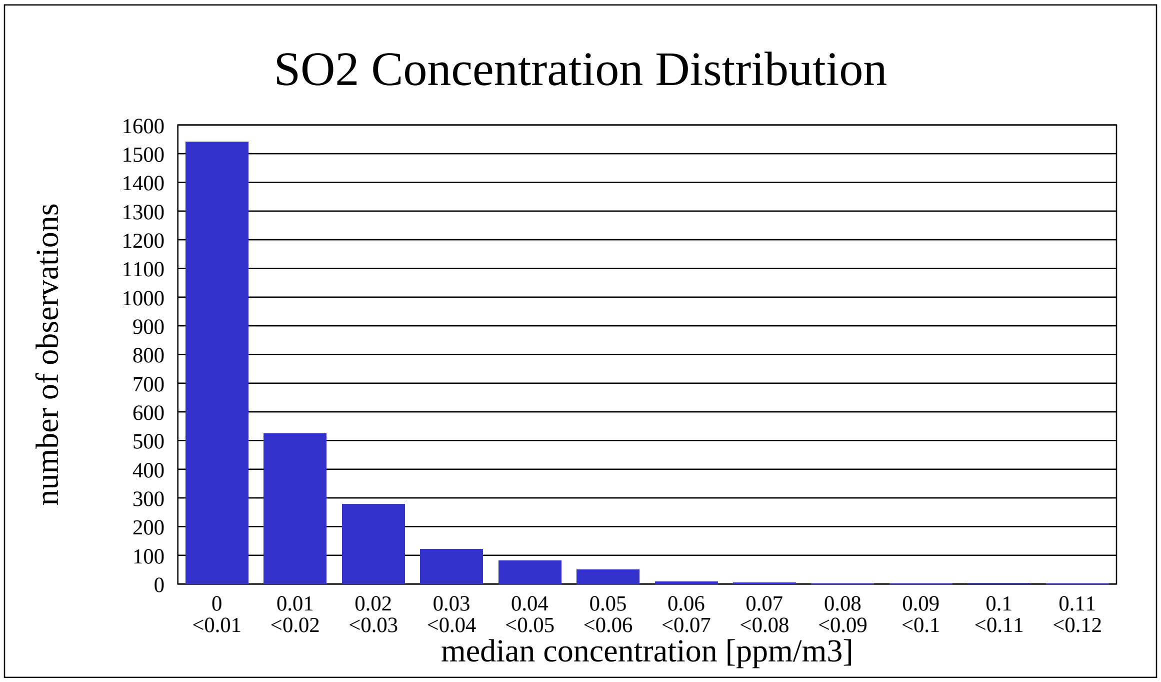

Figure A.2: Distribution of the Dependent Variable (logarithmic scale)

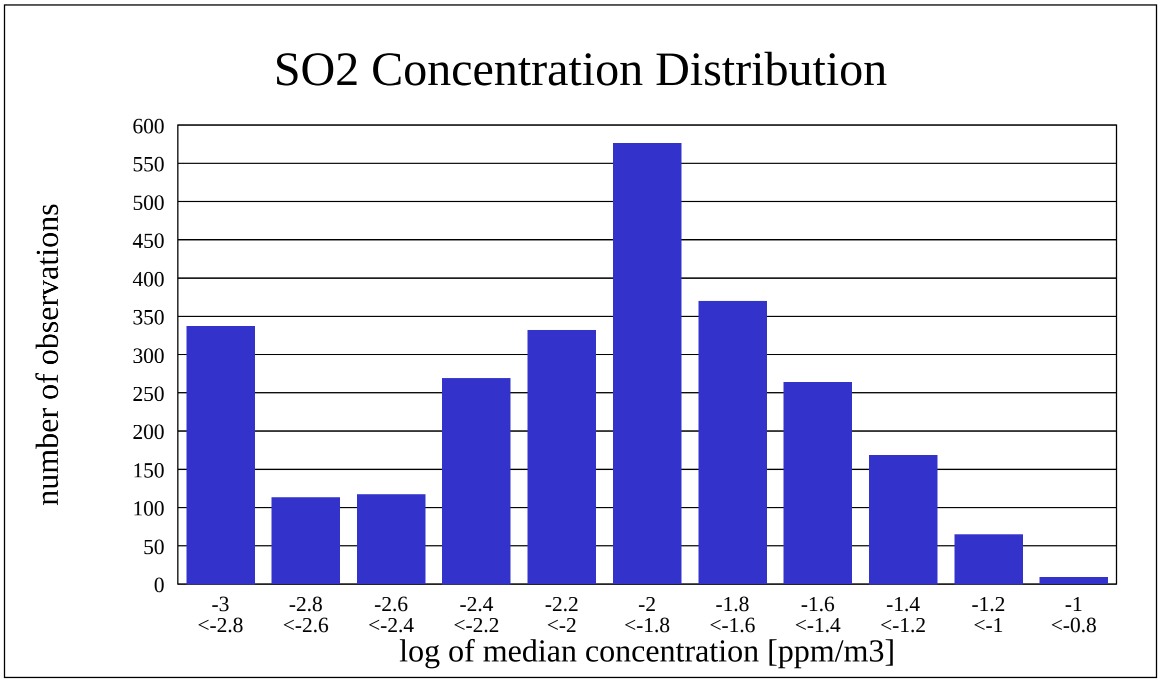

Figure A.3: Composition of GEMS/Air Data Set

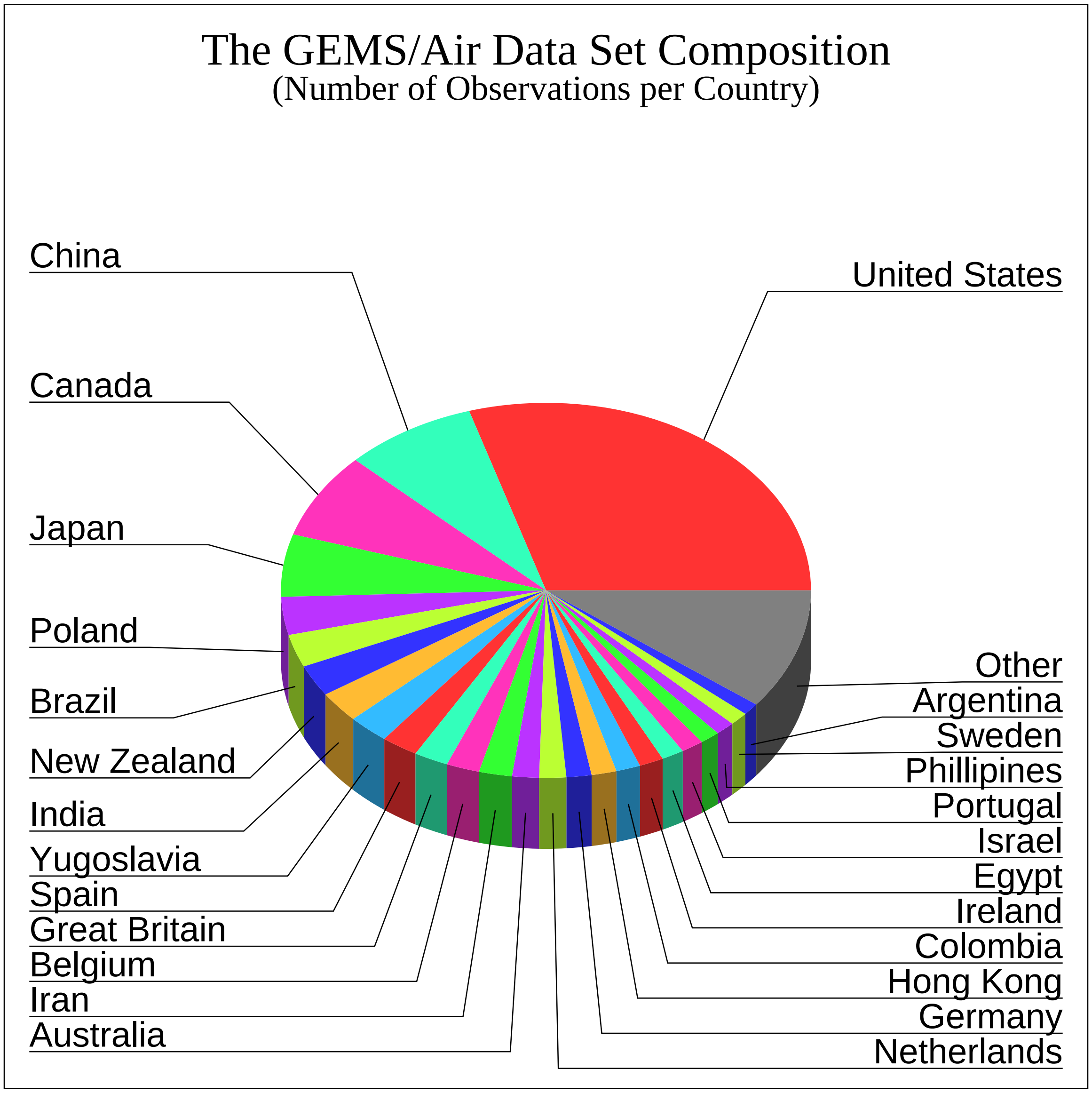

Figure A.4: GEMS/Air Participation by Country and Time Period
(Countries are sorted by decreasing number of contributing years)

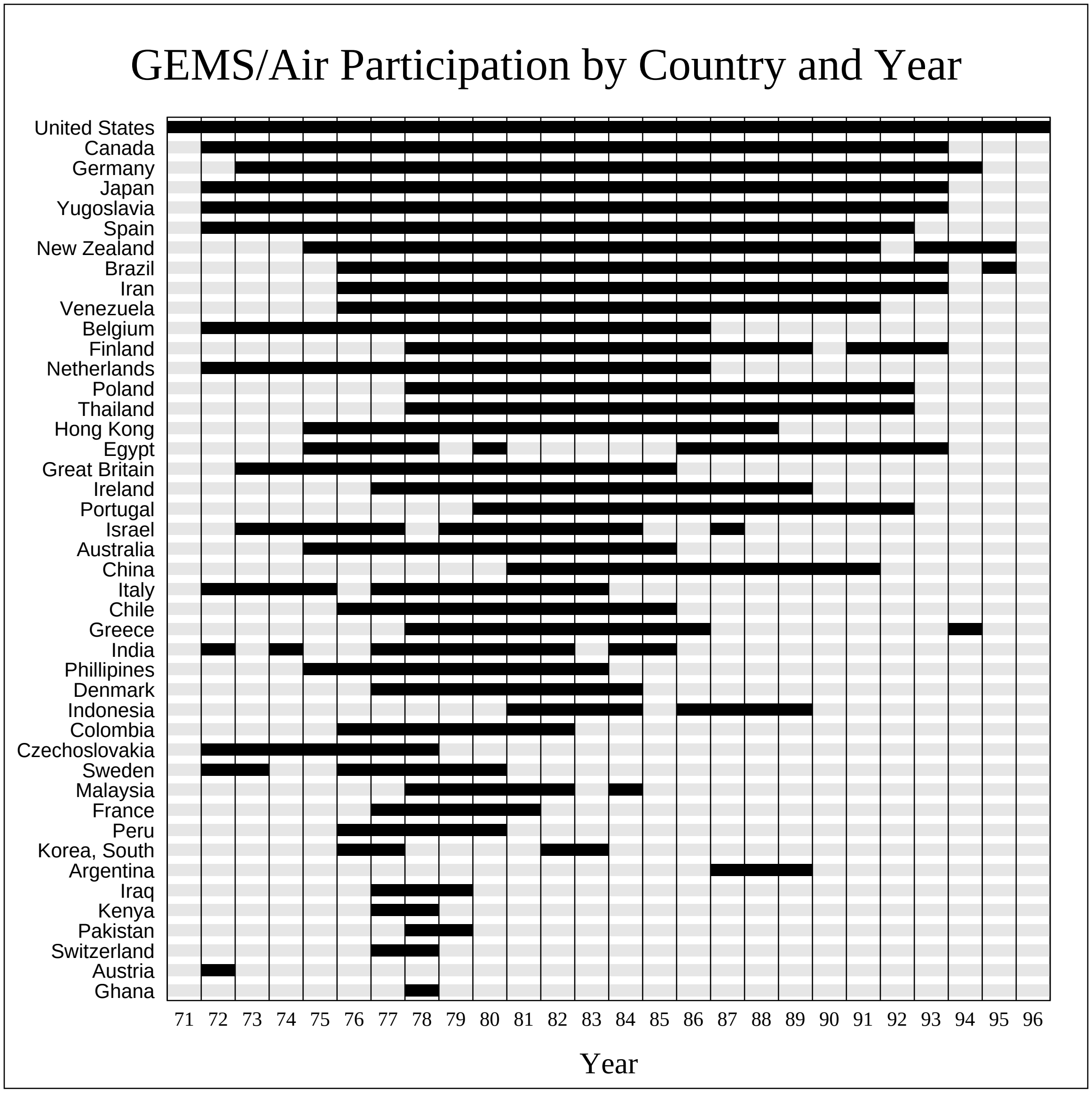

Table A.1: Cities by descending maximum of annual median SO_2 concentration

Country & City	n	min	max	Country & City	n	min	max	Country & City	n	min	max
KOR Seoul	6	25	115	CHE Zurich	1	17	26	USA Long Beach, CA	1	1	10
ITA Rome	3	2	103	IRL Dublin	3	4	26	USA Seattle, WA	1	1	10
ITA Milan	2	17	100	MYS Kuala Lumpur	4	1	25	NZL Auckland	3	1	9
YUG Zagreb	3	5	98	USA Alexandria, VA	1	5	25	IRQ Baghdad	3	1	8
IRN Tehran	3	7	93	POL Wroclaw	3	6	24	USA Chelsea, MA	1	4	8
CHN Shenyang	4	1	89	COL Medellin	3	1	22	USA Tampa, FL	3	1	8
AUT Vienna	3	40	80	ISR Tel Aviv	5	1	22	COL Cali	3	1	7
ESP Madrid	5	2	73	HKG Hong Kong	6	1	21	GHA Accra	3	4	6
CSK Prague	3	13	65	CAN Hamilton	5	1	20	THA Bangkok	4	1	6
BEL Brussels	4	9	64	CAN Montreal	4	1	20	USA Allen Park, MI	1	2	6
EGY Cairo	4	1	61	SWE Stockholm	5	1	20	USA St Ann, MO	1	4	6
GBR London	3	11	58	USA Philadelphia, PA	5	1	20	USA River Rouge, MI	1	3	6
JPN Tokyo	3	5	58	USA St Louis, MO	3	3	20	DEU Munich	1	5	5
JPN Osaka	4	5	56	CAN Vancouver	7	1	19	IDN Jakarta	3	1	5
CHN Guangzhou	4	2	55	PAK Lahore	2	15	19	PER Lima	3	1	5
BRA Sao Paulo	5	8	51	DNK Copenhagen	3	3	18	USA Atlanta, GA	2	2	5
PHL Manila	3	2	50	USA Detroit, MI	2	2	18	USA Waltham, MA	1	1	5
CHL Santiago	3	11	49	KEN Nairobi	2	7	17	PHL Davao	2	1	4
BRA Rio De Janeiro	2	20	46	USA Chester, PA	1	6	17	ARG Buenos Aires	1	1	3
CHN Beijing	5	1	44	NZL Christchurch	4	1	16	ARG San Lorenzo	1	2	3
CHN Xian	4	3	41	FRA Paris	3	2	15	USA Chula Vista, CA	1	1	3
CHN Shanghai	4	1	40	SWE Oxelosund	1	11	15	USA Dallas, TX	1	2	3
USA Boston, MA	2	3	40	USA Washington, DC	2	7	15	USA Livonia, MI	1	1	3
DEU Frankfurt	3	5	38	USA Cicero, IL	1	2	14	USA St Petersburg, FL	1	1	3
FRA Toulouse	4	19	38	VEN Caracas	3	3	14	USA Adams Co, CO	1	1	3
NLD Amsterdam	3	6	37	SWE Nykoping	2	5	13	USA Burbank, CA	1	1	2
IND Bombay	6	3	36	USA Chicago, IL	3	1	13	USA Los Angeles, CA	1	1	2
COL Bogota	3	1	35	USA East St Louis, IL	1	5	13	USA San Diego, CA	1	1	2
PRT Lisbon	3	1	35	POL Warsaw	3	3	12	USA Tarpon Springs, FL	1	1	2
IND Calcutta	3	4	33	USA Camden, NJ	1	5	11	ARG Cordoba	2	1	1
GBR Glasgow	3	11	32	USA Wood River, IL	1	2	11	ARG San Miguel de Tucuman	7	1	1
ARG Mendoza	3	10	30	CAN Toronto	5	1	10	ARG Santa Fe	1	1	1
AUS Melbourne	1	1	30	FIN Helsinki	3	1	10	ISR Ashdod	2	1	1
IND New Delhi	3	1	30	USA Baytown, TX	1	1	10	USA Azusa, CA	1	1	1
GRC Athens	5	7	29	USA Blue Island, IL	1	1	10	USA El Cajon, CA	1	1	1
USA New York City, NY	2	7	28	USA Denver, CO	1	2	10				
AUS Sydney	3	2	27	USA Houston, TX	3	1	10				

Note: The column n is the number of observation stations in each city. The columns min and max show the lowest and highest measured level of the annual median SO_2 concentration in each city, measured in parts per billion. Note that a maximum or minimum concentration of “1” is equivalent to the measurement threshold of the measurement device. Countries appear with their ISO-3166 codes.

	Health Organization. This package is provided by the U.S. Environmental Protection Agency (US-EPA) at http://www.epa.gov/airs/aexec.html. The US-EPA kindly provided a much more complete version of this dataset that included not only averages but also median and other percentiles of SO_2 concentrations. We would like to express our gratitude to Jonathan Miller of the US-EPA for providing additional GEMS/Air data not contained in the public release of the database, and for patiently answering our numerous technical questions. We had problems with the identification of several observation stations. The longitude and latitude information provided in one of the ancillary files was in some cases incorrect and was corrected case-by-case based on the the description of the location.
`PWT`	The **Penn World Tables** are described in Robert Summers and Alan Heston, "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950–1988", Quarterly Journal of Economics, Vol. 106, May 1991, pp. 327–368. Variables obtained from this data set include GDP per capita, population, capital stock per worker, and trade intensity. Note that the PWT do not contain data for Cuba; thus, this country was dropped from our analysis. The PWT data are available in revision 5.6 from the NBER ftp site at ftp://ftp.nber.org/pwt56/.
`CIESIN`	The Consortium for International Earth Science Information Network (CIESIN) **Global Population Distribution Database** contains the total population contained in each grid cell of $1^\circ \times 1^\circ$ in the year 1990 for each country. This data set is only available for this single year. It can be obtained freely from the United Nations Environmental Programme server maintained by the U.S. Geological Survey at http://grid2.cr.usgs.gov/globalpop/1-degree/description.html. The CIESIN data set was augmented by population counts of major urban agglomerations that is produced by the United Nations Population Division's 1996 Global Population Estimates and Projections database on Urban Agglomerations 1950–2015.[1] Additional data was obtained from the U.N. Demographic Yearbook (1994) and the Statistical Abstract of the United States (1994) to fill gaps in the data set.
`WRI`	The **World Resources Institute** publishes data on natural resources and physical endowments of countries. Data are published in "World Resources 1994-1995: A Guide to the Global Environment", Oxford University Press, Oxford:1995, and the subsequent "World Resources 1996-98" edition of this report. The WRI publishes the full set of data on diskette. Information is available at http://www.wri.org/.
`SACHS/WARNER`	The source for this data set is the NBER working paper by Jeoffrey Sachs and Andrew Warner acknowledged in the bibliogrpahy.
`BARRO/LEE`	The data set contains variables from the 1994 cross-country study by Robert J. Barro and Jong-Wha Lee. Data are presented either quinquennially for the years 1960-1985, i.e., 1960, 1965, 1970, 1975, 1980, and 1985, or for averages of five years' sub-periods over 1960-1985. This dataset is available from the NBER web

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[1] The Director, Population Division/DESIPA, United Nations, DC2-1950, New York, NY 10017, US

	site as a zip-ped archive at http://www.nber.org/pub/barro.lee/ZIP/BARLEE.ZIP; for more information, read http://www.nber.org/pub/barro.lee/README.TXT.
`GHCN`	Weather data was provided by the **Global Historical Climatology Network**. Information is available on monthly average temperatures, monthly precipitation, and atmospheric pressure. The first GHCN data base contains mean monthly temperature data (in tenths of degrees celsius) for 6039 stations throughout the world. The second GHCN data base contains total monthly precipitation data (in tenths of millimeters) for 7533 stations throughout the world. Most records (76%) end in the 1980s. No data are available for any station after 1990. To make the data usable for our project, the atmospheric pollution measurement stations were matched to their closest meteorological observation stations. Where two stations were nearby, an average of these two were formed. The raw data and description file are available from the National Climatic Data Center of the U.S. National Oceanic and Atmospheric Administration at ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/v1/.
`IMF/IFS`	The International Monetary Fund's "International Financial Statistics" provided ancillary data, mostly growth rates of real GDP and population, that were used to extrapolate data from the Penn World Tables.
`OIL`	Real world oil prices were obtained from the U.S. Energy Information Administration, a branch of the U.S. Dept. of Energy. The real world oil price is calculated by dividing the landed costs of crude oil imports from Saudi Arabia (Arabian Light) in US$ per barrel by the US GDP deflator (1990=100). More information is available at http://www.eia.doe.gov/price.html.
`A/C/T`	Longitude and Latitude data for the participating cities in the GEMS/Air study were hand-coded by the authors and were obtained primarily from the index of "Oxford Concise Atlas of the World", 2nd edition, Reed International Books, London, 1995.

A.3 Regressors

The following list of variables explains the content, method of construction, any modifications, and source of each of them.

`GDP_KM`	This measure is an approximation of the economic intensity of a city relative to its size ($/km^2). It is obtained by multiplying a country's per-capita GDP ($/person) by each city's population density (people/km^2). Extrapolations for per-capita GDP were carried out for the years past 1993 based on real growth rates obtained from the IMF/IFS statistics. Population densities were available only for 1990. Physical Unit: millions of 1995 US dollars per square kilometre. Dimensions: city by year. Sources: PWT, CIESIN.
`KL`	This is the capital abundance obtained from the physical capital stock per worker variable in the Penn World Tables. Physical Unit: thousands of 1995 US dollars.

	Dimensions: country by year. Source: PWT.
`RKL`	Relative capital abundance is variable KL divided by the corresponding world average for the given year, where “world average” is defined by all the countries in the Penn World Tables. Physical Unit: index number, world average equal to 1.0 Dimensions: country by year. Source: PWT.
`I`	This variable is the three-year average of lagged GDP per capita. That is, for a given year t, $I_t = (y_{t-1} + y_{t-2} + y_{t-3})/3$. Physical Unit: thousands of 1995 US dollars. Dimensions: country by year. Source: PWT.
`RI`	Relative income is variable I divided by the corresponding world average for the given year, where “world average” is defined by all the countries in the Penn World Tables. Physical Unit: index number, world average equal to 1.0 Dimensions: country by year. Source: PWT.
`SUB, RUR`	Suburban and rural location type dummy variables. The third (default) location type is central city. Note that GEMS/Air measurement stations are not all directly in metropolitan areas. In the GEMS/Air data set suburban and rural areas are only identified in the United States and China, comprising about 14% and 3% of all observations, respectively. Physical Unit: binary variable Dimension: observation site by year Source: GEMS/AIR.
`TI`	A country’s trade intensity is defined as the sum of exports and imports expressed as a percentage of gross domestic product. Physical Unit: percent Dimensions: country by year Source: PWT.
`BMP`	Black Market Premium of foreign exchange rate. Data are available for 1970 and 1980. Data for other years is interpolated linearly and extraploated by projecting the end-points flatly. Physical Unit: percent Dimensions: country by year Source: Barro-Lee (as obtained from issues of the World Currency Yearbook[2])

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[2] International Currency Data, Inc., 328 Flatbush Avenue, Suite 344, Brooklyn, NY 11238, U.S.A.

`TARIFF`	Average tariff rate on imports of intermediate goods and capital goods. This measure is an average for the time period 1985-88. Physical Unit: percent Dimensions: country Source: Sachs/Warner (originally: Barro/Lee (1994))
`QUOTA`	Coverage of quotas on imports of intermediates and capital goods. It is the own-import weighted nontariff frequency on capital goods and intermediates, based on licensing, prohibitions, and quotas. This measure is an average for the time period 1985-88. Physical Unit: percent Dimensions: country Source: Sachs/Warner (originally: Barro/Lee (1994))
`SW`	Sachs/Warner measure of openness. This measure is available for the entire time-period of our sample. This dummy variable is 1 for open economies and 0 if either of the following is true: (a) the country has a black market premium over 20%; (b) it is a socialist country as classified by Kornai (1992, table 1.1); (c) it had a score of 4 on the export marketing index in the World Bank study by Husain and Faruquee (1994, p. 238), or the QUOTA variable was greater than 0.4. Physical Unit: binary variable Dimensions: country by year Source: Sachs/Warner
`WT`	Average annual temperature. Physical Unit: degrees Celsius Dimensions: country by year Source: GHCN
`WP`	Coefficient of variation of monthly precipitation. This is calculated as the standard deviation of monthly precipitation in a given year divided by the monthly precipitation average in that given year. Physical Unit: dimensionless number Dimensions: country by year Source: GHCN
`OIL`	The real price of oil. Physical Unit: 1990-$ per barrel Dimensions: year Source: U.S. Department of Energy.
`HCOAL`	Hard coal reserves abundance. Physical Unit: PetaJoules per million workers Dimensions: country by year Source: WRI
`SCOAL`	Soft coal reserves abundance. Physical Unit: PetaJoules per million workers

	Dimensions: country by year Source: WRI
`C.C.`	Communist Country Dummy. This variable is equal to one if the country is either China, Czechoslovakia, Poland, or Yugoslavia. Physical Unit: binary variable Dimensions: country (for our sample there is no time variation) Source: A/C/T.
`TIME`	Years elapsed since 1980.

Summary statistics for the major variables appear in table A.2.

Table A.2: Summary Statistics

Variable	Dimension	Obs.	Mean	Std.Dev.
Log of SO2	log(ppm)	2621	-2.102	0.480
City Economic Intensity	\$m per km^2	2621	7.729	8.733
Capital abundance	\$k	2621	31.496	17.775
GDP per capita, 3yr avg.	\$k	2621	14.114	8.372
Trade Intensity	%	2621	41.054	31.859
Relative Income	World=1.00	2621	2.468	1.388
Relative (K/L)	World=1.00	2621	2.224	1.198
Communist Country	[—]	2621	0.147	0.354
C.C. $\times$ Income	\$k	385	3.669	2.403
Population Density	1000p/km^2	2621	0.615	0.549
Avg. Temperature	°C	2621	14.602	5.556
Precipitation Coeff. of Var.	[—]	2621	0.011	0.006

Note: All monetary figures are in 1995 US Dollars. The interaction term for income with the communist countries dummy only shows the case where the the dummy is equal to one; thus the mean for this line is the mean for the communist countries only. Population density is for each city in the year 1990.

Appendix B

Detailed Results

B.1 Capital Intensity and Pollution Abatement

Figure B.1 illustrates the relationship between capital intensity and the pollution abatement costs per unit of output ratio. A regression through the 122 data points based on the logarithmic transformations of abatement cost ratio and capital intensity reveals a positive relationship with an R^2 of 0.3, indicating that a 1% increase in the capital intensity increases the abatement cost ratio by 0.7%. Data were only available for manufacturing industries. Thus, a particularly interesting industry—electricity generation—is not included in the sample. From other sources it is known that pollution abatement costs and capital intensity are both extremely high in that industry.

B.2 More Results

Table B.1 reports the full set of estimates that corresponds to each of the regressions shown in abbreviated form in table 2.

B.3 Elasticities

Elasticities are calculated using the Delta method[1] for functions of the least squares estimator. Table B.2 presents estimated elasticities and their corresponding estimated standard errors for the trade intensity effect. The elasticities in table B.2 were evaluated at the sample mean (based on the 2621 observations in our sample), and two 10-year averages of trade intensity, relative income and relative capital abundance based on the periods 1975-84 and 1985-94. Table B.2 shows these elasticity calculations corresponding to the fixed-effects and random effects regression estimates shown in table 3.

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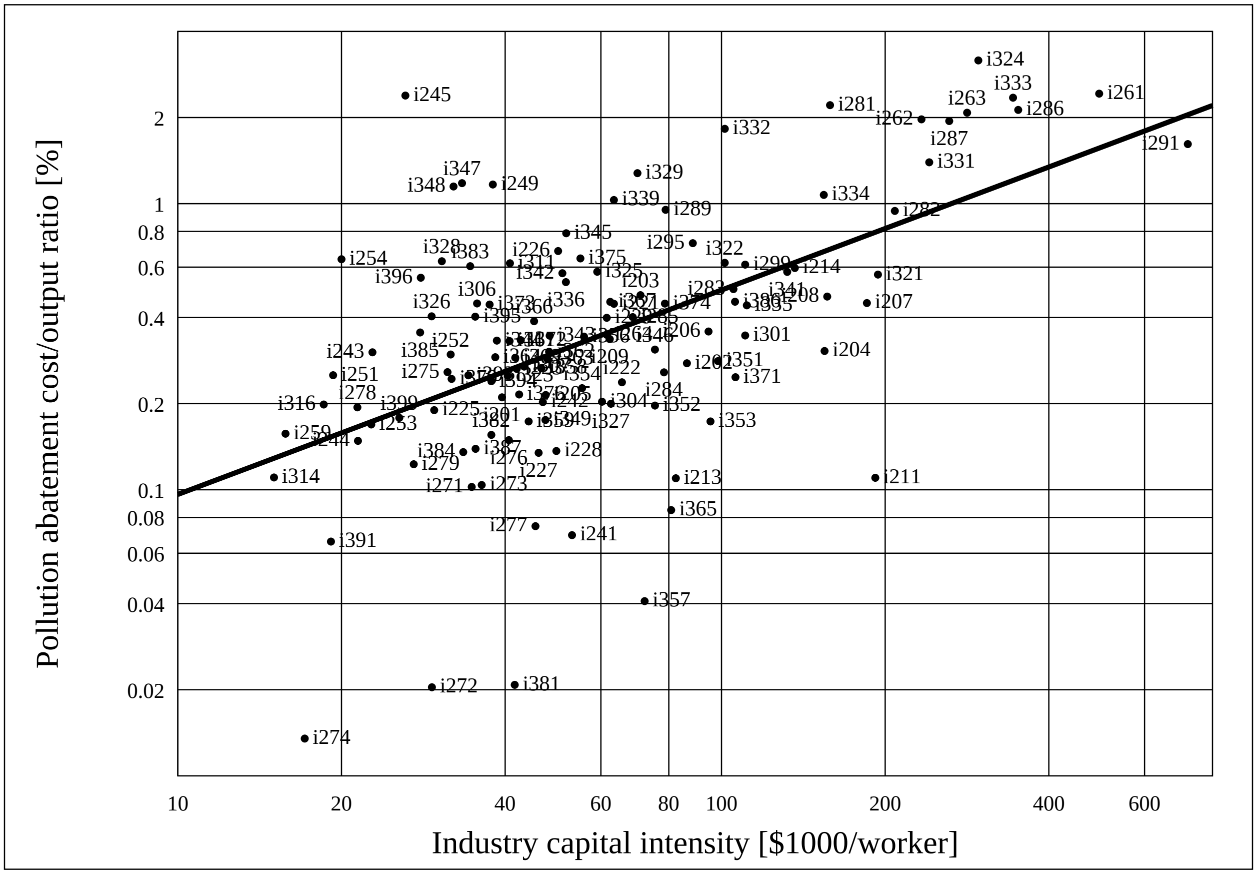
[1] See William H. Greene, "Econometric Analysis", third edition, Prentice-Hall: 1997, section 6.7.5, pp. 278ff.

Figure B.1: Pollution Abatement and Capital Intensity in the U.S. (1988)



Note: Pollution abatement data are as reported in Patrick Low "Trade Measures and Environmental Quality: The Implications for Mexico's Exports", chapter 7 in: Patrick Low (ed.) "International Trade and the Environment", World Bank Discussion paper 159, The World Bank, Washington/DC, 1992, pp. 113-114. Additional capital and labour figures for the 3-digit SIC manufacturing industries were taken from the U.S. Annual Survey of Manufacturing. The i123-type labels next to each data point indicate the 3-digit US-SIC industry.

Table B.1: Full Regression Results for Table 2

Model	T.I.	BMP	Tariff	Quota	S&W
θ =(X+M)/GDP in %	-0.00239				
Black Market Premium		0.02606			
Average Tariff (%)			0.00088		
Average Quota Equiv. (%)				0.00594	
Sachs&Warner Openness Dummy					0.03934
Intercept	-3.48199^{**}	-3.59011^{**}	-3.63178^{**}	-3.85865^{**}	-3.57350^{**}
GDP/km^2	0.05251^{**}	0.05401^{**}	0.05198^{**}	0.04787^{**}	0.05379^{**}
Capital abundance (K/L)	0.02780^{*}	0.02464	0.04028^{**}	0.04066^{**}	0.03158^{**}
$(K/L)^2$	-0.00049^{**}	-0.00047^{**}	-0.00056^{**}	-0.00055^{**}	-0.00053^{**}
Lagged p.c. income (I)	-0.12364^{**}	-0.12111^{**}	-0.16117^{**}	-0.13222^{**}	-0.14236^{**}
I^2	0.00288^{**}	0.00293^{**}	0.00399^{**}	0.00306^{**}	0.00336^{**}
Suburban	-0.52958^{**}	-0.47539^{**}	-0.57446^{**}	-0.60130^{**}	-0.46658^{*}
Rural	-0.77979^{*}	-0.72161	-0.83595^{*}	-0.87485^{*}	-0.71291
Communist Country	-0.06554	-0.03019	-7.04588^{*}	-6.93811^{*}	-0.00667
C.C. $\times$ I	0.18941	0.18223	8.82855^{*}	8.81603^{*}	0.17998
C.C. $\times$ I^2	-0.01512	-0.01559	-2.50989^{*}	-2.52996^{*}	-0.01456
Average Temperature	-0.05981^{**}	-0.05937^{**}	-0.05816^{**}	-0.05885^{**}	-0.05966^{**}
Precipitation Variation	4.25874	3.71501	5.36597	5.28258	4.27441
Time Trend	-0.03443^{**}	-0.03604^{**}	-0.04562^{**}	-0.04185^{**}	-0.03619^{**}
Observations	2621	2621	2369	2298	2621
Groups	293	293	270	263	293
R^2 (overall)	0.326	0.324	0.354	0.364	0.324

Note: T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Dependent variable is the log of the median of SO_2 concentrations at each observation site. Note that the black market premium, average tariff and quota coverage variables measure the *inverse* of openness; their sign has thus to be reversed to interpret the direction of the estimates as an increase in openness.

Table B.2: Country-Specific Elasticities from Baseline Regression

	Fixed Effects						Random Effects					
	Sample		1975–1984		1985–1994		Sample		1975–1984		1985–1994	
	η	s_η	η	s_η	η	s_η	η	s_η	η	s_η	η	s_η
ARG	-0.203^{**}	0.043	-0.137^{**}	0.039	-0.209^{**}	0.044	-0.106^{**}	0.026	-0.066^{**}	0.021	-0.108^{**}	0.027
AUS	-0.069	0.131	-0.067	0.131	-0.083	0.144	-0.036	0.091	-0.035	0.090	-0.042	0.101
AUT	-0.617^{**}	0.165	-0.595^{**}	0.215	-0.442	0.268	-0.376^{**}	0.101	-0.378^{**}	0.143	-0.288	0.182
BEL	-0.507	0.496	-0.462	0.505	-0.487	0.553	-0.342	0.334	-0.310	0.340	-0.320	0.373
BRA	-0.380^{**}	0.051	-0.429^{**}	0.055	-0.325^{**}	0.049	-0.226^{**}	0.035	-0.260^{**}	0.038	-0.186^{**}	0.033
CAN	-0.133	0.242	-0.209	0.217	0.035	0.293	-0.053	0.177	-0.104	0.161	0.063	0.208
CHE	5.042^{**}	1.407	5.003^{**}	1.403	6.185^{**}	1.665	3.515^{**}	0.847	3.494^{**}	0.843	4.317^{**}	1.004
CHL	-0.735^{**}	0.156	-0.718^{**}	0.155	-1.057^{**}	0.197	-0.372^{**}	0.102	-0.361^{**}	0.101	-0.562^{**}	0.130
CHN	-0.466^{**}	0.124	-0.333^{**}	0.089	-0.558^{**}	0.146	-0.224^{**}	0.086	-0.161^{**}	0.062	-0.269^{**}	0.102
COL	-0.901^{**}	0.111	-0.855^{**}	0.105	-0.919^{**}	0.118	-0.554^{**}	0.080	-0.525^{**}	0.076	-0.555^{**}	0.084
CSK	-1.120^{**}	0.147	-1.430^{**}	0.184	-1.632^{**}	0.217	-0.670^{**}	0.102	-0.862^{**}	0.128	-0.972^{**}	0.149
DEU	0.873^{*}	0.436	1.014^{*}	0.469	0.622	0.397	0.589^{*}	0.270	0.686^{**}	0.290	0.424	0.249
DNK	-0.375	0.221	-0.365	0.219	-0.354	0.223	-0.231	0.152	-0.224	0.151	-0.207	0.157
EGY	-0.886^{**}	0.317	-0.997^{**}	0.351	-0.861^{**}	0.310	-0.353	0.217	-0.404	0.241	-0.340	0.212
ESP	-0.510^{**}	0.099	-0.472^{**}	0.095	-0.567^{**}	0.116	-0.322^{**}	0.063	-0.293^{**}	0.059	-0.371^{**}	0.079
FIN	0.050	0.296	-0.047	0.283	0.273	0.296	0.026	0.194	-0.040	0.187	0.182	0.190
FRA	-0.210	0.145	-0.207	0.149	-0.178	0.161	-0.131	0.100	-0.127	0.102	-0.108	0.111
GBR	-0.248	0.153	-0.243	0.152	-0.214	0.147	-0.094	0.085	-0.091	0.085	-0.076	0.088
GHA	-0.325^{**}	0.106	-0.334^{**}	0.113	-0.698^{**}	0.239	-0.141	0.073	-0.141	0.078	-0.297	0.165
GRC	-1.046^{**}	0.148	-0.980^{**}	0.138	-1.178^{**}	0.166	-0.678^{**}	0.104	-0.634^{**}	0.097	-0.763^{**}	0.117
HKG	-0.244	0.578	-0.692	0.512	1.319	0.932	0.226	0.305	-0.123	0.270	1.534^{**}	0.588
IDN	-1.148^{**}	0.229	-1.065^{**}	0.253	-1.278^{**}	0.231	-0.613^{**}	0.160	-0.536^{**}	0.177	-0.703^{**}	0.162
IND	-0.308^{**}	0.088	-0.299^{**}	0.086	-0.350^{**}	0.103	-0.144^{**}	0.061	-0.140^{**}	0.060	-0.161^{*}	0.071
IRL	-1.819^{**}	0.306	-1.732^{**}	0.290	-1.626^{**}	0.310	-1.136^{**}	0.195	-1.070^{**}	0.183	-1.005^{**}	0.193
IRN	-0.582^{**}	0.089	-0.499^{**}	0.119	-0.621^{**}	0.078	-0.333^{**}	0.058	-0.247^{**}	0.071	-0.376^{**}	0.055
IRQ	-1.069^{**}	0.242	-1.300^{**}	0.225	-1.511^{**}	0.180	-0.570^{**}	0.136	-0.767^{**}	0.135	-0.940^{**}	0.130
ISR	-1.116^{**}	0.231	-1.168^{**}	0.242	-0.834^{**}	0.189	-0.717^{**}	0.152	-0.751^{**}	0.160	-0.508^{**}	0.114
ITA	-0.425^{**}	0.130	-0.417^{**}	0.139	-0.289^{*}	0.127	-0.276^{**}	0.087	-0.269^{**}	0.093	-0.184^{*}	0.086
JPN	-0.177^{**}	0.069	-0.233^{**}	0.072	-0.068	0.073	-0.110^{**}	0.046	-0.141^{**}	0.045	-0.042	0.050
KEN	-1.306^{**}	0.391	-1.164^{**}	0.352	-0.998^{**}	0.320	-0.596^{*}	0.272	-0.528^{*}	0.244	-0.440^{*}	0.222
KOR	-1.681^{**}	0.243	-1.693^{**}	0.244	-1.465^{**}	0.190	-0.975^{**}	0.169	-0.983^{**}	0.169	-0.912^{**}	0.129
MYS	-2.764^{**}	0.350	-2.596^{**}	0.334	-3.662^{**}	0.440	-1.675^{**}	0.245	-1.563^{**}	0.233	-2.307^{**}	0.313
NLD	-0.534	0.335	-0.529	0.338	-0.648	0.333	-0.338	0.229	-0.332	0.232	-0.407	0.227
NZL	-0.366	0.202	-0.345	0.205	-0.373	0.196	-0.236	0.137	-0.219	0.140	-0.245	0.133
PAK	-0.626^{**}	0.172	-0.659^{**}	0.183	-0.717^{**}	0.203	-0.297^{**}	0.120	-0.311^{**}	0.127	-0.334^{**}	0.140
PER	-0.931^{**}	0.134	-0.902^{**}	0.130	-0.677^{**}	0.106	-0.540^{**}	0.092	-0.523^{**}	0.089	-0.386^{**}	0.074
PHL	-0.928^{**}	0.225	-0.932^{**}	0.225	-1.153^{**}	0.285	-0.455^{**}	0.155	-0.458^{**}	0.156	-0.566^{**}	0.198
POL	-0.815^{**}	0.123	-0.951^{**}	0.137	-0.807^{**}	0.123	-0.468^{**}	0.080	-0.561^{**}	0.089	-0.459^{**}	0.082
PRT	-0.825^{**}	0.218	-0.691^{**}	0.194	-0.775^{**}	0.209	-0.387^{**}	0.131	-0.312^{**}	0.118	-0.368^{**}	0.121
SWE	-0.223	0.209	-0.258	0.224	-0.113	0.245	-0.126	0.148	-0.145	0.159	-0.056	0.170
THA	-0.917^{**}	0.263	-0.785^{**}	0.224	-0.992^{**}	0.283	-0.409^{*}	0.179	-0.355^{*}	0.154	-0.441^{*}	0.191
USA	-0.148	0.115	-0.139	0.104	-0.150	0.118	-0.074	0.090	-0.070	0.082	-0.075	0.093
VEN	-0.732^{**}	0.135	-0.635^{**}	0.133	-0.930^{**}	0.138	-0.460^{**}	0.086	-0.402^{**}	0.085	-0.575^{**}	0.089
YUG	-0.316	0.163	-0.195	0.155	-0.458^{**}	0.168	-0.079	0.101	-0.005	0.096	-0.171	0.105

Note: η and s_η are the estimate and standard error of the elasiticity. Significance at the 5% and 1% levels is indicated by a * and **, respectively. Countries appear with their ISO-3166 codes.

Appendix C

Sensitivity Analysis

We have subjected our model to a large array of sensitivity analyses. Section C.1 considers various alternatives of our “baseline” model with respect to the regressors and properties of the sample. Have we left our important variables? Is our model sensitive to the chosen time period? Section C.2 continues with a closer look at our dependent variable SO_2 concentration. What happens if we use a different concentration percentile rather than the median? Is there an alternative to using a logarithmic transformation? Finally, section C.3 addresses the question of simultaneity of determination of pollution concentrations and income. Can a simultaneous-equations approach provide additional insights?

C.1 Specification

Results presented in the main part of this paper are based on a regression model shown in table 3, hereafter referred to as the “baseline” model. To analyze the sensitivity of these results, we modify the right-hand side of our estimating equation to address potential problems and to introduce additional regressors. The results for four additional types of models are shown in tables C.1 and C.2 for fixed-effects and random-effects estimators, respectively.

The GEMS/Air study was carried out primarily throughout the years 1976-1991 when the United Nations Environment Programme (UNEP) provided funding to the participating countries. Before 1976 there are only few countries that provide measurements of SO_2 concentrations, and after 1991, the number of countries that report such observations drop rapidly. This is shown in table A.4. By 1996 data are only available from the United States. To allow for a possible participation bias due to funding, we repeat our baseline regression by excluding observations from before 1976 and from after 1991. This procedure reduces the number of observations by roughly 500, or 20%. None of the parameters that desribe scale, composition, technique, and openness effect change sign or significance except for the scale variable. In the fixed-effect model, the significance of the weather variables changes. We now find that a higher concentration of precipitation leads to higher pollution levels. This is consistent with our a-priori expectation that more frequent rain washes SO_2 out of the air.

A possible objection for using data from communist countries is that (a) they are not following a market mechanism and thus will not respond properly to changes in relative prices; and (b) consumers cannot induce the government to tighten pollution regulation. In the latter case, we would not find a technique effect. We already allowed for this possibility by isolating a communist-country technique effect. It turned out that we cannot identify a technique effect for these countries that is significantly different from zero. To address the unresponsiveness to market signals and allowing for a structural difference between communist and free-market countries, we delete all observations from communist countries and re-run our baseline regression. This procedure, which reduces the number of observations by roughly 15%, has only a marginal impact on our estimates.

Table C.1: Sensitivity Analysis for Specification — Fixed Effects

Model	Base	76-91	no C.C.	Res.	Yr-Dum
Intercept	-3.66165^{**}	-3.71228^{**}	-3.26725^{**}	-3.85849^{**}	-2.97686^{**}
Capital abundance (K/L)	0.11915^{**}	0.12270^{**}	0.11282^{**}	0.12387^{**}	0.12613^{**}
$(K/L)^2$	-0.00149^{**}	-0.00125^{**}	-0.00141^{**}	-0.00155^{**}	-0.00157^{**}
Lagged p.c. income (I)	-0.31075^{**}	-0.38240^{**}	-0.29617^{**}	-0.30190^{**}	-0.30690^{**}
I^2	0.00740^{**}	0.00840^{**}	0.00733^{**}	0.00733^{**}	0.00719^{**}
$\theta =$(X+M)/GDP in %	-0.02293^{**}	-0.04171^{**}	-0.03161^{**}	-0.02266^{**}	-0.02934^{**}
$\theta\times$ relative (K/L)	-0.03054^{**}	-0.02828^{**}	-0.02665^{**}	-0.02955^{**}	-0.03010^{**}
$\theta\times$ relative $(K/L)^2$	0.00592^{**}	0.00517^{**}	0.00530^{**}	0.00572^{**}	0.00591^{**}
$\theta\times$ relative income	0.03428^{**}	0.05181^{**}	0.03603^{**}	0.03352^{**}	0.03993^{**}
$\theta\times$ relative income sq.	-0.00523^{**}	-0.00915^{**}	-0.00551^{**}	-0.00497^{**}	-0.00635^{**}
GDP/km^2	0.04263^{**}	0.07546^{**}	0.04141^{**}	0.03990^{**}	0.04014^{**}
Communist Country					
C.C. $\times I$	1.15287^{**}	1.58590^{**}		1.04313^{**}	0.90379^{**}
C.C. $\times I^2$	-0.08355^{**}	-0.11097^{**}		-0.07471^{**}	-0.06426^{**}
Soft Coal (per worker)				0.00067	
Hard Coal (per worker)				0.00160	
Oil Price (real)				-0.00298^{*}	
Average Temperature	-0.05924^{*}	-0.04982	-0.06509^{*}	-0.05670^{*}	-0.05774^{*}
Precipitation Variation	7.96498	10.56087^{*}	6.59359	7.99755	10.77088^{*}
Time Trend	-0.03838^{**}	-0.04380^{**}	-0.04377^{**}	-0.04076^{**}	
Observations	2621	2114	2236	2621	2621
Groups	293	277	260	293	293
R^2 (overall)	0.137	0.122	0.157	0.114	0.159
Hausman Text	62.79	510.7	39.03	83.40	52.98

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is the log of the median of SO_2 concentrations at each observation site. Models are: Base = base regression from table 3; Time = time period is shortened to the main UNEP support period 1976-91 for the GEMS/Air project; no C.C. = communist countries are excluded; Res. = resource variables (hard coal, soft coal) and oil price are added; Yr-Dum = year dummies are entered instead of a linear time trend, but are not shown individually.

Table C.2: Sensitivity Analysis for Specification — Random Effects

Model	Base	76-91	no C.C.	Res.	Yr-Dum
Intercept	-3.05851^{**}	-2.96254^{**}	-2.66190^{**}	-3.00256^{**}	-2.34954^{**}
Capital abundance (K/L)	0.09194^{**}	0.08162^{**}	0.09431^{**}	0.09243^{**}	0.09195^{**}
$(K/L)^2$	-0.00123^{**}	-0.00090^{**}	-0.00112^{**}	-0.00125^{**}	-0.00126^{**}
Lagged p.c. income (I)	-0.29750^{**}	-0.31498^{**}	-0.34492^{**}	-0.29789^{**}	-0.30274^{**}
I^2	0.00687^{**}	0.00705^{**}	0.00796^{**}	0.00673^{**}	0.00717^{**}
θ =(X+M)/GDP in %	-0.01078^{*}	-0.01760^{**}	-0.01665^{**}	-0.01071^{*}	-0.01318^{**}
$\theta\times$ relative (K/L)	-0.02290^{**}	-0.02046^{**}	-0.02132^{**}	-0.02186^{**}	-0.02267^{**}
$\theta\times$ relative $(K/L)^2$	0.00427^{**}	0.00355^{**}	0.00365^{**}	0.00407^{**}	0.00430^{**}
$\theta\times$ relative income	0.02247^{**}	0.02845^{**}	0.02692^{**}	0.02119^{**}	0.02502^{**}
$\theta\times$ relative income sq.	-0.00330^{**}	-0.00480^{**}	-0.00410^{**}	-0.00291^{**}	-0.00394^{**}
GDP/km^2	0.05418^{**}	0.06800^{**}	0.05333^{**}	0.05685^{**}	0.05391^{**}
Communist Country	-0.45554	-0.65806		-0.18980	-0.19122
C.C. $\times$ I	0.30231	0.44469^{**}		0.18708	0.15558
C.C. $\times$ I^2	-0.02066	-0.03433^{*}		-0.00906	-0.00805
Soft Coal (per worker)				0.00323^{*}	
Hard Coal (per worker)				-0.00306	
Oil Price (real)				-0.00249	
Average Temperature	-0.06161^{**}	-0.06274^{**}	-0.07066^{**}	-0.06190^{**}	-0.06185^{**}
Precipitation Variation	3.98493	6.59084	4.03814	4.28667	5.00820
Time Trend	-0.03400^{**}	-0.03644^{**}	-0.04497^{**}	-0.03540^{**}	
Observations	2621	2114	2236	2621	2621
Groups	293	277	260	293	293
R^2 (overall)	0.343	0.291	0.367	0.352	0.358
Hausman Text	62.79	510.7	39.03	83.40	52.98

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is the log of the median of SO_2 concentrations at each observation site. Models are: Base = base regression from table 3; 76-91 = time period is shortened to the main UNEP support period 1976-91 for the GEMS/Air project; no C.C. = communist countries are excluded; Res. = resource variables (hard coal, soft coal) and oil price are added; Yr-Dum = year dummies are entered instead of a linear time trend, but are not shown individually.

In a further step, we introduce three new variables into our baseline model. Noting that there is typically a strong home bias in fuel consumption, we suspect that countries endowed abundantly with either hard coal or soft coal will rely to a larger extent on these fuel types. Reasons for a strong home bias could be (a) very high transportation costs; (b) substantial import barriers; or (c) local subsidization, directly or indirectly. Typically, soft coal contains a larger amount of sulphur than hard coal, but we expect a relative abundance of either soft or hard coal to increase the level of SO_2. To express relative abundance of these endowments (in a Heckscher-Ohlin sense), we divide the absolute level of endowment by the size of the workforce in each country. In the random-effects model we find a small (albeit insignificant) positive effect of soft coal abundance on pollution and a small negative effect of hard coal abundance on pollution. No clear results emerge from the fixed-effects model.

Another variable we introduce is the real price of oil. A higher price of oil should reduce the use of (sulphur-containing) oil. In fact, we can identify such a relationship in both the fixed-effects and random-effects model. However, on theoretical grounds the effect of a higher oil price on pollution is not necessarily as straight-forward as the above argument implies. If a higher oil price leads to a substitution effect and a switching from oil to other fuel types, it is uncertain if this other fuel is "cleaner" natural gas or "dirtier" coal. The data seem to suggest that the substitution is towards cleaner fuel types.

In another sensitivity test we replace the linear time trend by year dummies. Since we have an intercept in the model, we do not include dummies for the first two years (as there were very few observations for the very first year 1971). The result is surprisingly supportive of a linear time trend. The estimates for the year dummies (not shown in tables C.1 and C.2 in order to conserve space) trace out a remarkably stable linear path.

C.2 Dependent Variable

In a second set of sensitivity analyses we explore the choice of our dependent variable. We have argued before—based on the observations expressed in figures A.1 and A.2 that a logarithmic transformation of the dependent variable is appropriate. However, there is a menu of different SO_2 concentrations to choose from. We opted for the median SO_2 concentration because is more "robust" with respect to outlier observations than the arithmetic mean. The U.S. Environmental Protection Agency kindly supplied us with a variety of concentration statistics. We explore all of them in tables C.3 and C.4 for our fixed-effects and random-effects baseline model. In addition to the median ("Base"), we use the arithmetic mean ("Mean") and the 90th, 95th, and 99th percentile of SO_2 concentrations ("P90%", "P95%", and "P99%"). All of these measures were transfomred into logarithms when they were used as a dependent variable.

The first observation is that the intercept term is increasing from left to right, as the higher percentiles have higher average SO_2 concentrations. Comparing the mean with the median, we find a higher intercept for the mean. One way of reading this is that, adjusted for our regressors, the mean exceeds the median. This appears to be simply a result of the non-normal distribution of the (linear) SO_2 cocentrations, which we saw in figure A.1 to be highly-skewed to the left.

All five specifications produce results generate results thare are broadly in line with our previous findings. In particular, all signs remain the same, the estimates remain significant, and the overall magnitudes change only to a small extent. We take these results as a confirmation of the regularity

Table C.3: Sensitivity Analysis for Dependent Variable — Fixed Effects

Model	Base	Mean	P90%	P95%	P99%
Intercept	-3.66165^{**}	-3.41030^{**}	-2.61972^{**}	-2.10522^{**}	-1.65467^{**}
Capital abundance (K/L)	0.11915^{**}	0.11425^{**}	0.10939^{**}	0.10473^{**}	0.08089^{**}
$(K/L)^2$	-0.00149^{**}	-0.00159^{**}	-0.00159^{**}	-0.00147^{**}	-0.00120^{**}
Lagged p.c. income (I)	-0.31075^{**}	-0.27196^{**}	-0.27997^{**}	-0.29345^{**}	-0.23360^{**}
I^2	0.00740^{**}	0.00713^{**}	0.00758^{**}	0.00771^{**}	0.00659^{**}
$\theta =$(X+M)/GDP in %	-0.02293^{**}	-0.01402^{**}	-0.02570^{**}	-0.02284^{**}	-0.02155^{**}
$\theta\times$ relative (K/L)	-0.03054^{**}	-0.02401^{**}	-0.01895^{**}	-0.01725^{**}	-0.01501^{**}
$\theta\times$ relative $(K/L)^2$	0.00592^{**}	0.00551^{**}	0.00499^{**}	0.00428^{**}	0.00380^{**}
$\theta\times$ relative income	0.03428^{**}	0.01912^{**}	0.02047^{**}	0.01770^{**}	0.02000^{**}
$\theta\times$ relative income sq.	-0.00523^{**}	-0.00276^{**}	-0.00291^{**}	-0.00225^{*}	-0.00349^{**}
GDP/km^2	0.04263^{**}	0.04587^{**}	0.05505^{**}	0.04885^{**}	0.03623^{**}
Communist Country					
C.C. $\times$ I	1.15287^{**}	0.99146^{**}	1.20225^{**}	1.21931^{**}	1.12806^{**}
C.C. $\times$ I^2	-0.08355^{**}	-0.07040^{**}	-0.08613^{**}	-0.08602^{**}	-0.08445^{**}
Average Temperature	-0.05924^{*}	-0.06309^{**}	-0.06268^{**}	-0.06767^{**}	-0.06887^{**}
Precipitation Variation	7.96498	6.89432^{*}	6.45666^{*}	7.01900^{*}	7.34888^{*}
Time Trend	-0.03838^{**}	-0.03964^{**}	-0.04209^{**}	-0.04434^{**}	-0.04417^{**}
Observations	2621	2621	2621	2621	2621
Groups	293	293	293	293	293
R^2 (overall)	0.137	0.167	0.170	0.165	0.150
Hausman Text	62.79	97.59	126.9	131.8	89.14

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is as specified in the Model line: Base = the log of the median of SO_2 concentrations at each observation site; Mean = the log of the arithmetic mean of SO_2 concentrations; P90%, P95%, P99% = the log of the 90th, 95th, and 99th percentiles of SO_2 concentrations.

Table C.4: Sensitivity Analysis for Dependent Variable — Random Effects

Model	Base	Mean	P90%	P95%	P99%
Intercept	-3.05851^{**}	-3.13931^{**}	-2.38088^{**}	-2.03715^{**}	-1.82329^{**}
Capital abundance (K/L)	0.09194^{**}	0.09604^{**}	0.09313^{**}	0.09017^{**}	0.07120^{**}
$(K/L)^2$	-0.00123^{**}	-0.00134^{**}	-0.00133^{**}	-0.00127^{**}	-0.00109^{**}
Lagged p.c. income (I)	-0.29750^{**}	-0.28014^{**}	-0.29176^{**}	-0.28955^{**}	-0.22264^{**}
I^2	0.00687^{**}	0.00687^{**}	0.00735^{**}	0.00737^{**}	0.00639^{**}
$\theta =$(X+M)/GDP in %	-0.01078^{*}	-0.00748^{*}	-0.01406^{**}	-0.01363^{**}	-0.01284^{**}
$\theta\times$ relative (K/L)	-0.02290^{**}	-0.02052^{**}	-0.01804^{**}	-0.01731^{**}	-0.01576^{**}
$\theta\times$ relative $(K/L)^2$	0.00427^{**}	0.00425^{**}	0.00393^{**}	0.00365^{**}	0.00343^{**}
$\theta\times$ relative income	0.02247^{**}	0.01724^{**}	0.01928^{**}	0.01861^{**}	0.02060^{**}
$\theta\times$ relative income sq.	-0.00330^{**}	-0.00258^{**}	-0.00290^{**}	-0.00274^{**}	-0.00385^{**}
GDP/km^2	0.05418^{**}	0.05156^{**}	0.05731^{**}	0.05077^{**}	0.03901^{**}
Communist Country	-0.45554	-0.39216	-0.38129	-0.49986	-0.34550
C.C. $\times$ I	0.30231	0.37737^{**}	0.45852^{**}	0.48635^{**}	0.47876^{**}
C.C. $\times$ I^2	-0.02066	-0.02622^{*}	-0.03289^{**}	-0.03476^{**}	-0.03963^{**}
Average Temperature	-0.06161^{**}	-0.04965^{**}	-0.05018^{**}	-0.05370^{**}	-0.05632^{**}
Precipitation Variation	3.98493	6.96624^{*}	8.00871^{**}	8.87576^{**}	8.99548^{**}
Time Trend	-0.03400^{**}	-0.03569^{**}	-0.03817^{**}	-0.04021^{**}	-0.04193^{**}
Observations	2621	2621	2621	2621	2621
Groups	293	293	293	293	293
R^2 (overall)	0.343	0.323	0.286	0.259	0.226
Hausman Text	62.79	97.59	126.9	131.8	89.14

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is as specified in the Model line: Base = the log of the median of SO_2 concentrations at each observation site; Mean = the log of the arithmetic mean of SO_2 concentrations; P90%, P95%, P99% = the log of the 90th, 95th, and 99th percentiles of SO_2 concentrations.

of the distribution of SO_2 concentrations. Recall that these numbers are *annual* summary statistics that tend to mitigate the effect from single-day outliers.

We have argued earlier that the appropriate transformation of the dependent variable is to take the logarithm, based on our observations expressed in figure A.2. However, in table C.5 we explore the possibility of other transformations, notably, a linear transformation and a Box-Cox transformation. All of these are based on our fixed-effects model.

We apply a Box-Cox transformation as a generalization to our fixed-effects model (where ν_i is a site-specific fixed effect). The model can be specified as

$$y_{it}^{(\lambda)} \equiv \left\{ \begin{array}{ll} y_{it} - 1 & \text{for } \lambda = 1 \\ (y_{it}^{\lambda} - 1)/\lambda & \text{for } 0 < \lambda < 1 \\ \log(y_{it}) & \text{for } \lambda = 0 \end{array} \right\} = \mathbf{X}_{it}\beta + \nu_i + \epsilon_{it} \tag{C.1}$$

which assumes that there exists a λ for a transformation of the dependent variable so that $\epsilon_{it} \sim \mathrm{N}(0, 1)$. The transformation parameter λ is determined by maximizing the concentrated log-likelihood function

$$L(\lambda) = -\frac{N}{2} \ln \hat{\sigma}^2(\lambda) + (\lambda - 1) \sum_t \ln(y_t) \tag{C.2}$$

where

$$\hat{\sigma}^2(\lambda) = \frac{1}{N} \left(y^{(\lambda)} - \mathbf{Xb} \right)' \left(y^{(\lambda)} - \mathbf{Xb} \right) \tag{C.3}$$

With the results from the Box-Cox regression we can also peform two likelihood-ratio tests, $2[L(\lambda) - L(0)] \sim \chi^2(1)$ and $2[L(\lambda) - L(1)] \sim \chi^2(1)$, that allow us to test the Box-Cox transformation against the log-linear (our baseline) model and the simple linear model.

We find that the signs of our estimates remain stable and significant. The optimal Box-Cox transformation parameter is approximately 0.2. When we test this specification against either the log-linear or pure-linear case, the log-likelihood test statistics reject both the log-linear and pure-linear specifications in favour of the Box-Cox transformation. Observe, though, that the pure-linear model is rejected by a much larger margin than the log-linear model. Also note that the interpretation of the parameters changes and cannot be compared across the three models.

C.3 Simultaneity

Yet another concern in our work has been the possibility of a simultaneous determination of pollution and (current-period) per-capita income. We did not pursue a simultaneous-equations approach for our main analysis because it is our belief that the likely effect of pollution on per-capita income is rather small. This belief appears to be validated by Dean (1998), who finds no significant relationship in her 2SLS procedures. Contemporaneous per-capita income only enters through our scale variable but not through our technique variable; recall that we use lagged per-capita income to determine the technique effect because income increases will typically take a number of years to translate into policy changes.

To address the simultaneity of income (y) and pollution (z) determination in our scale effect we have experimented with a fixed-effects 2-stage least squares estimator using as a second estimating equation a simple approximation of a production function

$$\log(y) = \gamma_1 \log(z) + \gamma_2 \log(K) + \gamma_3 \log(L) + \gamma_4 (t - 1980) \tag{C.4}$$

Table C.5: Sensitivity Analysis for Dependent Variable Transformation

Model	Base	linear	Box-Cox
Intercept	-3.66165^{**}	33.52426^{**}	4.77272^{**}
Capital abundance (K/L)	0.11915^{**}	2.22034^{**}	0.21781^{**}
$(K/L)^2$	-0.00149^{**}	-0.02131^{**}	-0.00256^{**}
Lagged p.c. income (I)	-0.31075^{**}	-6.49089^{**}	-0.56817^{**}
I^2	0.00740^{**}	0.14208^{**}	0.01327^{**}
θ =(X+M)/GDP in %	-0.02293^{**}	-0.10291	-0.02994^{**}
$\theta\times$ relative (K/L)	-0.03054^{**}	-0.37748^{**}	-0.05071^{**}
$\theta\times$ relative $(K/L)^2$	0.00592^{**}	0.05532^{**}	0.00942^{**}
$\theta\times$ relative income	0.03428^{**}	0.35264^{**}	0.05298^{**}
$\theta\times$ relative income sq.	-0.00523^{**}	-0.05865^{**}	-0.00836^{**}
GDP/km^2	0.04263^{**}	0.82573^{**}	0.07352^{**}
Communist Country			
C.C. $\times$ I	1.15287^{**}	8.71297^{**}	1.65554^{**}
C.C. $\times$ I^2	-0.08355^{**}	-0.66355^{*}	-0.11982^{**}
Average Temperature	-0.05924^{*}	-0.55303	-0.08790^{*}
Precipitation Variation	7.96498	-54.65010	7.99823
Time Trend	-0.03838^{**}	-0.67198^{**}	-0.06789^{**}
Observations	2621	2621	2621
Groups	293	293	293
R^2 (overall)	0.137	0.184	0.109
λ			0.218
LR Test $\chi^2(1)$	230^{**}	2685^{**}	

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. λ is the transformation parameter of the Box-Cox transformation as defined in equation (C.1). The likelihood ratio test statistics are explained in section C.2.

where K and L denote capital stock and labour force, and t is a linear time trend. In addition, we decompose a city's economic intensity measure into the product of per-capita income and population density. Taking logs of the resulting expression, we can additively separate these two effects in our regression equation. As our measure of population density is constant over time, it does not appear as a regressor in the fixed-effects implementation. In contrast to our baseline model, the estimated coefficient corresponding to income is a constant-elasticity estimation of the scale effect.

Results from the fixed-effects 2SLS regression, shown in table C.6, indicate that the parameters in our baseline model remain stable. However, we estimate the scale effect from a city's economic intensity to be much higher than in our baseline model: around 2. In the GDP regression we find that pollution has a negligible (negative) effect on per-capita income with an estimated elasticity of 0.03, ie, a 10% increase in pollution will decrease per-capita income by 0.3%. The elasticities for the composition and trade intensity effects (as usual evaluated at sample means) are consistent with our other work. The technique-effect elasticity is much higher in magnitude (around –3.2). Consistent with our other empirical work the sum of scale and technique effect remains negative.

Table C.6: Simultaneity Analysis: 2SLS Regression

Dependent Variable	$\ln(\text{SO}_2)$	
log of country GDP p.c.	2.22844^{**}	(3.12)
Capital abundance (K/L)	0.14139^{**}	(7.91)
$(K/L)^2$	-0.00150^{**}	(6.92)
Lagged p.c. income (I)	-0.50473^{**}	(5.02)
I^2	0.00980^{**}	(5.89)
C.C. $\times I$	0.78348^{**}	(2.77)
C.C. $\times I^2$	-0.06749^{**}	(3.10)
θ =(X+M)/GDP in %	-0.02679^{**}	(3.94)
$\theta\times$ relative (K/L)	-0.02306^{**}	(3.95)
$\theta\times$ relative $(K/L)^2$	0.00420^{**}	(3.40)
$\theta\times$ relative income	0.02471^{**}	(3.52)
$\theta\times$ relative income sq.	-0.00268	(1.63)
Average Temperature	-0.04648	(1.93)
Precipitation Variation	9.23458^{*}	(2.24)
Time Trend	-0.05551^{**}	(9.07)
R^2	0.143	

Dependent Variable	$\ln(\text{GDP})$	
log of SO_2 concentration	-0.02788^{*}	(2.26)
log of capital stock	0.46416^{**}	(24.41)
log of labour fource	-0.71942^{**}	(15.64)
Time Trend	0.00578^{**}	(4.60)
R^2	0.731	

Elasticities		
Scale	2.228^{**}	(3.12)
Composition	1.483^{**}	(4.83)
Technique	-3.218^{**}	(3.80)
Trade Intensity	-0.518^{**}	(4.84)

Note: T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Regression is a fixed-effects modification of 2SLS (ie, site averages have been subtracted).