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Is Free Trade Good for the Environment

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This paper investigates 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 effects created by trade imply a net reduction in pollution from these sources. Combining our estimates of scale, composition and technique effects yields a somewhat surprising conclusion: freer trade appears to be good for the environment. (JEL F11, Q25)

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 sim-

ple factor endowment hypothesis, suggests that dirty capital-intensive processes will 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 that trade flows are primarily determined by factor endowment considerations and apparently not by differences in pollution abatement costs. Does this mean that trade has no effect on the environment?

This paper investigates how "openness" to international 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 sulfur dioxide concentra-

tions 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 percent, then pollution concentrations fall by about 1 percent. Free trade is good for the environment.[1]

We obtain this conclusion by estimating a very simple model highlighting the interaction of factor endowments and income differences in determining the pattern of trade. Our approach, while relatively straightforward, is novel in four 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.[2] Grossman and Krueger (1993) 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. Our estimates indicate that a 1 percent increase in the scale of economic activity raises pollution concentrations by 0.25 to 0.5 percent for an average country in our sample, but the accompanying increase in income drives concentrations down by 1.25–1.5 percent via a technique effect.

Second, we devise a method for determining how trade-induced changes in the composition of output affects pollution concentrations. Many empirical studies include some measure of openness to capture the impact trade has in altering the composition (and hence the cleanliness) of national output, but there is very little reason to believe that openness affects the composition of output in all countries similarly. Both the pollution haven hypothesis and the factor endowment hypothesis predict that openness to trade will alter the composition of national output in a manner that depends on a nation's comparative advantage.

For example, under the pollution haven hypothesis, poor countries get dirtier with trade while rich countries get cleaner.[3] As a result, simply adding openness to trade as an additional explanatory variable for pollution (across a panel of both rich and poor countries) is unlikely to be fruitful. Instead we look for trade's effect by conditioning on country characteristics. We find that openness conditioned on country characteristics has a highly significant, but relatively small, impact on pollution.

Third, we show how to combine economic theory with our estimates of scale, composition and technique effects to arrive at an assessment of the environmental impact of freer trade. Grossman and Krueger's influential study of NAFTA presented an argument based on the relative strength of these same three effects, but their estimate of the composition effect of trade was obtained from methods and data unrelated to their complementary work estimating the relative strength of scale and technique effects. Moreover, their evidence on composition effects was specific to the situation of Mexico. Here we estimate all three effects jointly on a dataset that includes over 40 developed and developing countries.

And lastly, our approach forces us to distinguish between the pollution consequences of income growth brought about by increased openness from those created by capital accumulation or technological progress. We find that income

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[1]Free trade appears to lower sulfur dioxide concentrations for an average country in our sample, but may of course worsen the environment through other channels. Our evidence is specific to sulfur dioxide, however sulfur dioxide emissions are highly correlated with other airborne emissions.

[2]For example, income transfers across countries raise national income but not output, whereas foreign direct investment raises output more than national income. To evaluate the environmental consequences of either we need separate estimates of technique and scale effects.

[3]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. See for example Proposition 2.

gains brought about by further trade or neutral technological progress tend to lower pollution, while income gains brought about by capital accumulation raise pollution. The key difference is that capital accumulation necessarily 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.[4]

The theoretical literature on trade and the environment contains many papers where pollution policy differences across countries drive pollution-intensive industries to countries with lax regulations.[5] 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 investigated how income-induced differences in pollution policy determine trade patterns. While this earlier work produced several insights, it ignored the 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. The model contains as one limiting case the canonical Heckscher-Ohlin-Samuelson model of international trade and as another limiting case a simple pollution haven model. Consider-

ing these two motivations for trade is especially important in an empirical investigation, because many of the most polluting industries are also highly capital intensive.[6] Moreover, it allows us to examine whether changes in dirty goods production brought about by trade are better explained by factor abundance motives or by pollution haven motives arising from an unequal distribution of world income.

The empirical literature in this area has progressed in three distinct ways. One influential group of studies asks "how does economic growth affect the environment?". This literature was initiated by early work by Grossman and Krueger (1993, 1995) and has since produced a sizeable and fast growing empirical literature examining what has come to be known as the "Environmental Kuznets curve."[7] Many of these studies also investigate the role of trade by adding a measure of openness as an additional regressor. The defining feature of this literature is its lack of explicit theory. Although the results from these studies are often interpreted within the context of scale, composition and technique effects, they do not provide separate estimates of their magnitudes.

Our work is most closely related to this branch of the literature, but differs in that we employ an explicit theoretical model to guide our estimation, we present separate estimates of scale, composition and technique elasticities, and we provide a methodology for adding up these effects to assess the environmental implications of freer trade. Despite the fact that this earlier work lacks a formal theory, some of their conclusions receive support in our work. Most notably, Grossman and Krueger's (1993) study of NAFTA had at its core the argument that technique effects offset scale effects—at least for Mexico—and that the composition effect created by further US-Mexico trade was likely to

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[4]Another more speculative implication of our results is that pollution concentrations should at first rise and then fall with increases in income per capita, if capital accumulation becomes a less important source of growth as development proceeds.

[5]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.

[6]See Mani and Wheeler (1997) and Antweiler et al. (1998), appendix section B.1 for evidence linking capital intensity and pollution intensity.

[7]Some authors refer to it as the Grossman-Krueger Kuznets Curve. Other early contributions to this literature are Shafik (1994) and Selden and Song (1994).

be driven more by factor endowment considerations than by differences in environmental regulation. Our work supports these conclusions: income effects appear to be economically and statistically significant, and the trade-induced composition effects are not driven by differences in pollution regulations.

There is a second group of studies examining the link between the costs of pollution abatement costs and trade flows. This approach was pioneered by Tobey (1990), and was employed in the context of the NAFTA agreement by Grossman and Krueger (1993).[8] This branch of the literature asks a slightly different question: "how do environmental regulations effect trade flows?" Nevertheless some of their results are also relevant to our work. For example, a common result from these studies is that measures of environmental stringency have little affect on trade flows. This result immediately casts doubt on the pollution haven hypothesis, which holds that trade in dirty goods primarily responds to cross-country differences in regulations. While our work is quite different in approach and method, we too find little support for the pollution haven hypothesis. We do not infer from this, however, that the cost of regulations doesn't matter to trade flows; instead we suggest it is because other offsetting factors more than compensate for the costs of tight regulation in developed economies.

Finally there are those studies that employ either the U.S. Toxic Release Inventory, U.S. emission intensity data, or simple rules to categorize goods industries as dirty or clean, to construct measures of the toxic (or pollution) intensity of production and trade flows. Work along these lines includes Low and Yeats (1992), Lucas et al. (1992) and Mani and Wheeler (1997). The strength of this branch of the literature is its broad cross-country coverage; its weakness is that this coverage arises from the construction of data under various assumptions regarding the similarity of emission intensities across countries. This literature typically asks "how has the pollution intensity of exports or production changed over time?" By comparing the answer to this question across countries differing in development level, income, or trade stance, the authors hope to identify links between various policy options, country characteristics, and environmental outcomes. While this work is useful in documenting trends in the pollution intensity of output and production, it cannot answer why these trends exist. Our work differs from this method by using theory to identify those factors we believe to be crucial to environmental outcomes, and by using regression analysis to hold all else equal when evaluating the links between country characteristics and environmental outcomes.

The overall impression one gets from this literature is that while there are many interesting findings, a consensus view does not exist - and the path to building such a consensus view is unclear. The unsettled nature of the literature arises at least in part because existing studies are hamstrung by the lack of a well-defined theory. This naturally makes inference difficult. Additional difficulties arise because good data on pollution levels are scarce, and even the best data reflect not only anthropogenic influences but also the little understood natural processes of dispersion and absorption. As a consequence, our simple first-generation pollution and trade model carries a heavy burden in providing us with the structure needed to isolate and identify the implications of international trade. While this is a concern, we suggest that earlier empirical investigations failed to find a strong and convincing link between environmental outcomes and freer trade precisely because they lacked a strong theoretical underpinning. With a more complete theoretical framework to guide us we are able to look in the "right directions" for trade's effect. Moreover, our simple pollution demand-and-supply model may play a useful role in focusing future efforts in this area.

The rest of the paper is organized as follows. In section I we develop a relatively simple general equilibrium model of trade to determine how a fall in trade barriers affects pollution levels. In section II we then describe our

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[8]Levinson (1996) reviews this work.

strategy for dealing with econometric difficulties and present our estimating equation. In section III we present our empirical results. Section IV concludes. Appendices A and B contain proofs of propositions and a description of our data. An additional Technical Appendix available on request from the authors contains further supporting materials.

I. Theory

A. 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 $c^Y(w, r)$. Let Y be the numeraire, and denote the relative price of X by p. Since countries differ in their location, proximity to suppliers and existing trade barriers, domestic prices will not be identical to world prices. Accordingly we write,

$$p = \beta p^w \qquad (1)$$

where β measures the importance of trade frictions and p^w is the common world relative price of X. Note $\beta > 1$ if a country imports X and $\beta < 1$ if a country exports X.[9]

Pollution Abatement

We denote pollution emissions by Z. Pollution is generated by X production, but firms have access to an abatement technology. Abatement is costly but uses the same factor intensities as all other activities in the X industry. Hence we simply treat units of X as inputs into abatement.

If a firm has a gross output of x units, and allocates x_a units to abatement, then its net output is $x_n = x(1 - \theta)$, where $\theta = x_a/x$ is a measure of the intensity of abatement. If pollution is proportional to output and abatement is a constant returns activity, then we can write pollution emissions as:

$$z = e(\theta)x \qquad (2)$$

where $e(\theta)$ is emissions per unit of X produced and is decreasing in θ.[10] We assume abatement is worthwhile ($e'(0) = -\infty$), but with physical limits ($e(1) > 0$).

The government uses pollution emission taxes to reduce pollution. Given the pollution tax τ, the profits π^x for a firm producing X are given by revenue less factor payments, pollution taxes, and abatement costs. Using (1) and our definition of θ, we may write profits succinctly as:

$$\pi^x = p^N x - wL_x - rK_x \qquad (3)$$

where $p^N = p(1-\theta) - \tau e(\theta)$ is the net producer price for gross output. Because of constant returns, the output of an individual firm is indeterminate, but for any level of output, the first order condition for the choice of θ implies:

$$p = -\tau e'(\theta) \qquad (4)$$

Hence, we have $\theta = \theta(\tau/p)$ with $\theta' > 0$ and we can write emissions per unit output as:

$$e = e(\tau/p) \qquad (5)$$

where $e' < 0$. The production side equilibrium conditions are simply (2), (4) and the standard zero profit and full employment conditions:

$$p^N = c^X(w, r) \qquad 1 = c^Y(w, r)$$
$$K = c_r^X x + c_r^Y y \qquad L = c_w^X x + c_w^Y y \qquad (6)$$

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[9] For example, let v be the level of iceberg transport costs (that is $v < 1$ 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 $p^d = vp^w$, and if the good is imported, we have $p^d = p^w/v$. Freer trade (an increase in v) raises p^d if X is exported and lowers p^d if X is imported.

[10] When x units of gross output are produced, and x_a units are devoted to abatement, emissions are given by $E(x_a, x)$. Given our assumptions, E is decreasing in x_a, increasing in x, strictly convex in x_a, and linearly homogenous in x and x_a together. Convexity in abatement inputs follows from diminishing returns to the variable factor and implies increasing marginal abatement costs. Linear homogeneity follows from constant returns. Using the linear homogeneity of E, we then write $E(x_a, x) = e(\theta)x$.

Consumers

For most of our analysis, consumers differ only in their preferences over pollution. There are two groups in society: N^g Green consumers who care greatly about the environment (Greens), and $N^b = N - N^g$ Brown consumers (Browns) who care less about the environment. Each consumer maximizes utility, treating pollution as given. For simplicity, we write the indirect utility function of a consumer in the ith group as:

$$V^i(p, G/N, z) = u\left(\frac{G/N}{\rho(p)}\right) - \delta^i z \quad (7)$$

for $i = \{g, b\}$ and where $\delta^g > \delta^b \geq 0$, G is national income (so G/N is per capita income), $\rho(p)$ is a price index, and u is increasing and concave. Implicit in (7) is the assumption of homothetic preferences over consumption goods. Pollution is a pure public bad, but Greens suffer a greater disutility than Browns. It is now convenient to define real per capita income as $I = [G/N]/\rho(p)$ and rewrite indirect utility as simply $u(I) - \delta^i z$.

Government

We model the policy process very simply. We assume the government chooses a pollution tax to maximize a weighted sum of the each group's preferences. It solves:

$$\max_\tau N \left[\lambda V^g + (1 - \lambda)V^b\right] \quad (8)$$

where λ is the weight put on Greens. λ may vary across governments.[11] We introduce this formulation to allow for the realistic possibility that government behavior varies across countries (perhaps across Communist and noncommunist countries), while allowing for an endogenous link between pollution policy and economic conditions.

[11] For example, if the government is utilitarian, then $\lambda = N^g/N$; if the government is controlled by the Greens $\lambda = 1$, and if controlled by Browns, $\lambda = 0$.

The optimal pollution tax maximizes the weighted sum of utilities in (8) subject to private sector behavior, production possibilities, fixed world prices and fixed trade frictions (see however section III.E for a consideration of optimal tariffs). Private sector behavior can be represented by a standard GNP function giving maximized private sector (net of tax) revenue as $R(p^N, K, L)$.[12] Overall income is private sector revenue plus rebated taxes $G = R(p^N, K, L) + \tau z$. The first order condition yields

$$u'(I)\frac{dI}{d\tau} - \left[\lambda\delta^g + (1 - \lambda)\delta^b\right]\frac{dz}{d\tau} = 0.$$

With world prices fixed we have:

$$\begin{aligned} \frac{dI}{d\tau} &= \frac{1}{N\rho(p)}\left[R_{p^N}\frac{dp^N}{d\tau} + z + \tau\frac{dz}{d\tau}\right] \\ &= \frac{\tau}{N\rho(p)}\frac{dz}{d\tau} \end{aligned}$$

Rearranging our first order condition now yields an amended Samuelson rule:

$$\tau = N[\lambda MD^g(p, I) + (1 - \lambda)MD^b(p, I)] \quad (9)$$

where $MD^i(p, I) = \delta^i \rho(p)/u'$ is marginal damage per person, and $MD_I^i > 0$ given the concavity of the utility function. Simplifying slightly allows us to rewrite (9) as:

$$\tau = T\phi(p, I) \quad (10)$$

We refer to $T = \lambda N\delta^g + (1-\lambda)N\delta^b$ as "country type" and $T\phi(p, I)$ as effective marginal damage (MD). Pollution policy therefore varies with economic conditions and government type.

B. Pollution Demand and Supply

Our model yields a relatively simple reduced form linking pollution emissions to a short list of (predetermined) economic factors. To isolate the role of trade, it is important to understand how these different economic factors affect the demand for, and supply of, pollution. To do so, we use the terminology of scale, composition and technique effects. We start by noting

[12] See Woodland (1982) and Dixit and Norman (1980).

the private sector's demand for pollution is implicitly defined by (2). To rewrite this demand in a more convenient form for empirical work, we define an economy's scale as the value of national output at base-year world prices. In obvious notation, our measure of scale, S, is:

$$S = p_x^0 x + p_y^0 y \qquad (11)$$

Choosing units so that base-year prices are unity, we now write pollution emissions as

$$z = ex = e\varphi S \qquad (12)$$

where φ is the share of X in total output. Equation (12) provides a simple decomposition: pollution depends on the pollution intensity of the dirty industry, $e(\theta)$, the relative importance of the dirty industry in the economy, φ, and the overall scale of the economy, S. In differential form:

$$\hat{z} = \hat{S} + \hat{\varphi} + \hat{e} \qquad (13)$$

where hats denote percent change. The first term is the scale effect. It measures the increase in pollution generated if the economy were simply scaled up, holding constant the mix of goods produced, φ, and production techniques, $e(\theta)$. For example, if all endowments of the economy grew by 10 percent, and if there was no change in the composition of output or emission intensities, then we should expect to see a 10 percent increase in pollution. The second term in (13) is the composition effect. If we hold the scale of the economy and emissions intensities constant, then an economy that devotes more of its resources to producing the polluting good will pollute more. Finally we have the technique effect, captured by the last term. All else constant, an increase in the emission intensity will increase pollution.

We will use a quantity index of output to measure the scale effect. But because a change in prices creates opposing composition and technique effects, it is necessary to divide each into its more primitive determinants. Using (6) we can solve for the share of X in total output, φ, as a function of the capital/labor ratio $\kappa = K/L$, the net producer price p^N and base-year world

prices (suppressed here). That is, the composition of output is $\varphi = \varphi(\kappa, p^N)$, and we have the composition effect given by:

$$\hat{\varphi} = \varepsilon_{\varphi\kappa}\hat{\kappa} + \varepsilon_{\varphi p}\hat{p}^N \qquad (14)$$

where the elasticity of φ with respect to κ and p^N are both positive. Next differentiate p^N and employ (1) and (4) to find:

$$\hat{p}^N = \left(\hat{\beta} + \hat{p}^w\right)(1+a) - a\hat{\tau} \qquad (15)$$

where $a = e(\theta)\tau/p^N$. Similarly, using (1) and (5) we find:

$$\hat{e} = \varepsilon_{e,p/\tau}\left(\hat{\beta} + \hat{p}^w - \hat{\tau}\right) \qquad (16)$$

where the elasticity of emission intensity with respect to p/τ is positive.[13] Combining (13)-(16) we obtain a decomposition of the private sector's demand for pollution,

$$\begin{aligned}
\hat{z} = {}& \hat{S} + \varepsilon_{\varphi,\kappa}\hat{\kappa} + \left[(1+a)\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}\right]\hat{\beta} \\
& + \left[(1+a)\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}\right]\hat{p}^w \\
& - \left[a\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}\right]\hat{\tau} \qquad (17)
\end{aligned}$$

All elasticities are positive. If we draw this derived demand in $\{z, \tau\}$-space, then (17) shows that an increase in scale, capital abundance or the world price of dirty goods shifts the pollution demand curve to the right. A movement of β towards one captures a reduction in trade frictions. But since β is greater than one for a dirty good importer this implies $\hat{\beta} < 0$; and since β is less than one for a dirty good exporter, a reduction in trade frictions implies $\hat{\beta} > 0$. Therefore, a reduction in trade frictions shifts the pollution demand curve to the right for a dirty good exporter, but to the left for a dirty good importer.

Increases in the pollution tax reduce the quantity demanded of pollution through two channels. First they lower the demand for pollution by raising abatement and lowering the emissions per unit of X produced. This is captured

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[13]It is convenient to define elasticities so that they are positive. Note that e is decreasing in τ/p, and therefore increasing in p/τ.

by the elasticity $\varepsilon_{e,p/\tau} > 0$. Second, higher pollution taxes lower the producer price of X and induce a shift in the composition of output that lowers X output for any given emissions intensity. The strength of this effect depends on the importance of pollution taxes in the net producer price (a), and the elasticity of φ with respect to a change in producer prices, $\varepsilon_{\varphi,p}$.

Pollution supply is in effect given by government policy that sets the price for polluting. From (1), and (10) we obtain a decomposition of pollution supply:

$$\hat{\tau} = \hat{T} + \varepsilon_{MD,p}\hat{\beta} + \varepsilon_{MD,p}\hat{p}^w + \varepsilon_{MD,I}\hat{I} \quad (18)$$

where $\varepsilon_{MD,p} > 0$ and $\varepsilon_{MD,I} > 0$. If we draw (18) in $\{z, \tau\}$-space, then increases in real income, relative prices, or country type shift the pollution supply curve upwards. For example, if Greens are given a greater weight in social welfare, or become a larger fraction of the population over time, then policy becomes more stringent and pollution supply shifts upwards. Similarly, an increase in real income will increase the demand for environmental quality and shift up the pollution supply curve. An increase in the world relative price of X makes consumption of market goods more expensive relative to environmental protection. This creates a pure substitution effect towards more environmental protection, reflected in (18) by $\varepsilon_{MD,p} > 0$. As a result pollution supply shifts up. An identical substitution effect is at work when trade frictions fall.

A Reduced Form

Combining supply in (17) and demand in (18) yields a simple reduced form linking pollution emissions to a small set of economic factors.

$$\hat{z} = \pi_1\hat{S} + \pi_2\hat{\kappa} - \pi_3\hat{I} + \pi_4\hat{\beta} + \pi_5\hat{p}^w - \pi_6\hat{T} \quad (19)$$

where all π_ι are positive, and none of the right hand side variables are determined simultaneously with emissions. Two features of (19) warrant further comment. First, since a change in domestic prices shifts pollution supply and

demand in opposing directions, it is not obvious that π_4 and π_5 are positive. We evaluate this claim more formally in Proposition 1 below. Second, we claim "a reduced form" links emissions to our economic factors despite the fact that emissions and these same factors are clearly endogenous variables. In our framework, emissions are determined endogenously, but recursively. As a result, the factors on the right hand side of (19) are not simultaneously determined with, or by, the level of emissions.[14] This feature of our simple general equilibrium model has the benefit of providing us a simple, straightforward, and parsimonious reduced form linking pollution emissions to economic determinants. We evaluate our first claim below.

The Trade-Induced Composition Effect

Proposition 1 *Consider two economies that differ only in their trade frictions: (i) if both countries export the polluting good, then pollution is higher in the country with lower trade frictions; (ii) if both import the polluting good, then pollution is lower in the country with lower trade frictions.*

Proof: See Appendix A

Proposition 1 isolates the *trade-induced composition effect*. The sign of this composition effect differs across countries. For an exporter of the polluting good, β rises with freer trade and this raises the relative price of the dirty good X.

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[14]To see this note that $R(p^N, K, L) + \tau z = p(1-\theta)x + y$ which is independent of z. Next, note that (4), (6), (10) solve for I, τ and θ, given world prices. With τ, θ and p determined, p^N is given. Outputs are determined by p^N, and z follows from $z = e(\theta)x$. This result follows for two reasons. First a society may decide to spend some of its potential income on improving environmental quality and the remainder on consumption goods—but higher pollution does not *cause* higher real income. Second, because marginal damage is independent of z, the equilibrium level of emissions does not affect the pollution tax. As a result, a change in emissions does not cause second order changes in the composition of output or our measures of scale and income. As a result of these two features, real income, scale and the pollution tax are set simultaneously while emissions are set recursively.

This shifts a dirty good exporter's pollution demand curve to the right and shifts its pollution supply curve up. Pollution demand shifts out for two reasons: the composition of national output shifts towards X; and emission intensities rise because abatement inputs are now more costly. The shift in the pollution supply curve dampens this increase in pollution as the pure substitution effect of the goods price increase leads the government to raise the pollution tax. However, the direct demand side effects swamp the substitution effect in supply, and pollution rises.[15] Consequently, holding all other determinants of pollution supply and demand constant, emissions must rise. This increase in emissions represents the trade-induced composition effect for a dirty good exporter.

In contrast, β falls with freer trade for an importer of the polluting good. This raises the relative price of the clean good Y, and again shifts both pollution demand and supply. Demand side determinants dominate and emissions fall. This reduction in emissions represents the trade-induced composition effect for a clean good exporter.

Proposition 1 therefore implies that if we look across all countries and hold other determinants of emissions constant, we should not expect to find openness per se related in any systematic way to emissions. While Proposition 1 is useful, it is limited in two respects. First although it isolates the trade-induced composition effect, any fall in trade frictions will alter the scale of output and income per capita of the liberalizing country as well. Therefore, to account for the full environmental impact of a fall in trade frictions we must also account for the accompanying scale and technique effects. Proposition 1 captures the partial effect of trade liberalization; an overall assessment needs the full effect. Second, the results from the Proposition

are conditional on trade patterns, but the Proposition itself is silent on the determinants of trade patterns. We treat each of these issues in turn below.

FIGURE 1
A DIRTY GOOD EXPORTER
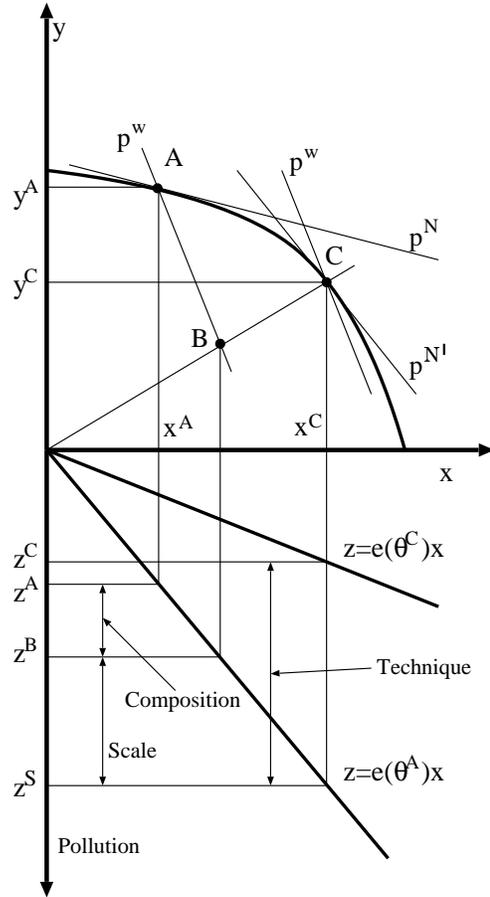
The Full Impact of Openness

To find the full impact of a change in trade frictions we must account for the change created in real incomes, the scale of output, and its composition. Differentiate (12) with respect to β, holding world prices, country type, and factor endowments constant, to find:

$$\frac{dz}{d\beta}\frac{\beta}{z} = \pi_1\frac{dS}{d\beta}\frac{\beta}{S} - \pi_3\frac{dI}{d\beta}\frac{\beta}{I} + \pi_4 \quad (20)$$

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[15]To see this note that the increase in τ is less than proportional to the increase in β, since the increase in τ induced by β is a pure substitution effect which is proportional to the share of X in consumption (which is less than one). This ensures both that emission intensity e rises, and that the share of X in production rises. Details are in the appendix.

A fall in trade frictions produces a scale effect, a technique effect, and the trade-induced composition effect discussed above. To understand how these three effects interact to determine the environmental consequences of trade, we employ Figure 1.

In the top panel of Figure 1 we depict the production response of a dirty good exporter to a fall in trade frictions. In the bottom panel we depict the pollution consequences of these changes. Before the reduction in trade frictions, production is at point A, the world price is p^w and the net price is p^N. We have assumed this country is an exporter of the dirty good and therefore has consumption at a point to the north-east of A along the economy's budget constraint (not drawn). Note that the value (in world prices) of domestic output at A measures this economy's scale. In the bottom panel we depict the equilibrium pollution level both before and after the fall in trade frictions. Recall that $z = e(\theta)x$. Hence when production is at A, and emissions intensity is $e(\theta^A)$, pollution is given by z^A.

When trade frictions fall the domestic price approaches the world price and production moves to point C at the new producer price of $p^{N'}$. At C, real income is higher and there is a change in the techniques of production. The emissions intensity falls to $e(\theta^C)$ and overall pollution falls to z^C. Our methodology divides the movement from z^A to z^C into three component parts. First, holding both the scale of the economy and the techniques of production fixed, trade creates a change in the composition of output given by the movement from A to B. Corresponding to this movement is the increase in pollution from z^A to z^B in the bottom panel. This is the trade-induced composition effect isolated in Proposition 1.

The movement in the top panel from point B to point C is the scale effect. The increase in pollution from z^B to z^S in the bottom panel gives the pollution consequences of this scale effect. Finally, note that the value of output measured at world prices rises because of trade and this real income gain (indirectly) creates the technique effect shown in the bottom panel. The

technique effect is the fall in pollution from z^S to z^C as producers switch to cleaner techniques with lower emissions intensity.

In total the diagram shows that trade liberalization for a dirty good exporter leads to less pollution if the composition and scale effects are overwhelmed by the technique effect. Since this is only a possibility and not a necessity within our model we formalize our results in Proposition 2.

Proposition 2 *Consider a small reduction in trade frictions for our small open economy, then:*
(i) if the small open economy exports the clean good, the full effect of this trade liberalization is to lower pollution emissions;
(ii) if the small open economy exports the dirty good and the elasticity of marginal damage with respect to income is below one, then the full effect of this trade liberalization is to raise its pollution emissions;
(iii) if the small open economy exports the dirty good and the elasticity of marginal damage with respect to income is sufficiently above one, then the full effect of this trade liberalization is to lower its pollution emissions.

Proof: See Appendix A.

The first part of the proposition concerns dirty good importers. For dirty good importers the trade-induced composition effect is negative and since X production falls, the sum of composition and scale effects must also be negative.[16] Consequently, pollution emissions will fall for a dirty good importer. For a dirty good exporter, both the trade-induced composition effect and the scale effect are positive. Pollution demand shifts right from these two forces, and Proposition 2 indicates that if the policy response is sufficiently weak (an elasticity of marginal damage with respect to income less than one) emissions will rise. That is, the upward shift in pollution

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[16]This is a product of our two good model. With many polluting goods the scale effect may dominate the composition effect leading to a rise in pollution from these two sources.

supply is overwhelmed by the demand shifts. Alternatively, if the elasticity of marginal damage is sufficiently strong, then emissions will fall as the technique effect dominates. The full effect of a trade liberalization differs from the partial effect because of two additional effects, and because these new effects can be strong enough to overwhelm the composition effect.

C. Adding up Scale, Composition and Technique Effects

The amount of information required to implement an adding-up exercise akin to (20) is great. In our empirical work we develop estimates for π_1, π_3 and π_4. But even with these estimates in hand we are faced with disentangling the effects of trade liberalization on income growth from all other potential sources. Since attempts to link trade to growth and income levels are the subject of an already large and somewhat controversial literature, we do not attempt to measure trade's effect on GDP ($dS/d\beta$) or GNP per person ($dI/d\beta$). Instead we employ economic theory to add up our estimated scale, composition and technique effects. Taking factor endowments as fixed, a lowering of transport costs or trade barriers raises the value of domestic output and real income in a small open economy. The value of output and income rise by the same percentage and this creates both scale and technique effects.[17] Therefore, we can simplify (20) slightly and write:

$$\frac{dz}{d\beta}\frac{\beta}{z} = [\pi_1 - \pi_3]\frac{dI}{d\beta}\frac{\beta}{I} + \pi_4 \qquad (21)$$

In some circumstances we can add up these three effects to come to an overall assessment of trade without knowledge of trade's effect on income or scale. For example, consider a dirty good exporter. Note $dI/d\beta$ is positive since an increase in β represents lower trade frictions. If we find $\pi_1 > \pi_3$ and $\pi_4 > 0$, then we conclude trade liberalization raises pollution for a dirty

[17]If GNP differs from GDP because of receipts or payments from abroad, then we would need to correct for the (generally small) share of these payments in GNP.

good exporter: scale effects dominate technique and the trade-induced composition effect is positive. Under these same circumstances, trade liberalization would have an ambiguous effect on emissions for a clean good exporter. Consequently, even to implement our more limited adding-up exercise, it is necessary to ask who exports dirty goods, and why?

Pollution Haven versus Factor Abundance Motives

In our model comparative advantage is primarily a function of relative factor abundance and relative incomes. While limiting cases of our model reflect only pollution haven motives or pure factor endowment motives, in general we expect both determinants of comparative advantage to matter. To investigate further, we solve for autarky prices. Let $RD(p)$ denote the demand for good X relative to good Y. Then the relative price of good X is determined by the intersection of the (net) relative supply and demand curves

$$RD(p) = (1 - \theta)\chi(\kappa, p^N) \qquad (22)$$

where $\chi = x/y$ is determined from (6), and net relative supply is $(1 - \theta)\chi$. Totally differentiating, using (15), (16) and (18), and rearranging gives an expression linking autarky prices to real income and endowments:

$$\hat{p} = \frac{\varepsilon_{MD,I}\left[a\varepsilon_{\chi,p^N} + \frac{\theta}{1-\theta}\varepsilon_{\theta,\tau/p}\right]\hat{I} - \varepsilon_{\chi,\kappa}\hat{\kappa}}{\Delta} \qquad (23)$$

where all elasticities and Δ are positive. Equation (22) shows that in general, the pattern of trade is determined by both factor abundance and income-driven differences in pollution policy. For example, unless both the dirty and clean sectors use identical factor proportions then $\varepsilon_{\chi,\kappa}$ is not zero and capital abundance matters to comparative advantage. Similarly, if the environment is a normal good, then $\varepsilon_{MD,I}$ is nonzero and real income matters as well.

The role of factor endowments

Standard factor endowment theories predict capital abundant countries export capital-intensive goods. In our model this need not be true because pollution policy can reverse this pattern of trade. Nevertheless, capital abundance is still a key determinant 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 (23) we obtain $\hat{p} < 0$ since $\varepsilon_{\chi,\kappa} > 0$. All else equal, an increase in the abundance of the factor used intensively in the pollution-intensive sector increases the likelihood that a country will be an exporter of pollution-intensive goods. We can show that if the country is *sufficiently* capital abundant, it must export the capital intensive (polluting) good:

Proposition 3 *Suppose the world price p^w is fixed. Then, for a given level of real income I, there exists $\underline{\kappa}$ such that if $\kappa > \underline{\kappa}$, then Home exports X. Moreover, for such a country, the trade-induced composition effect will be positive.*

Proof: See Appendix A.

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 lax pollution policy, and rich countries have a comparative advantage in clean goods because of their stringent pollution policy.[18] 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 richer countries will have stricter pollution policy and this will lead to a comparative advantage in clean goods. Using (23) we obtain $\hat{p} > 0$ whenever $\hat{I} > 0$. When countries differ in factor endowments and income levels, we can show

that if the country is *sufficiently* rich, it must export the labor-intensive (clean) good.

Proposition 4 *Suppose the world price p^w is fixed and there exists an ε such that $\varepsilon_{MD,I} > \varepsilon > 0$. Then, for a given level of the capital/labor ratio κ, there exists $\underline{I}$, such that if $I > \underline{I}$, then Home exports Y. Moreover, for such a country, the trade-induced composition effect will be negative.*

Proof: See Appendix A.

From Theory to Estimation

Proposition 1 contains a very simple message: comparative advantage matters. If we compare countries with similar incomes and scale, openness should be associated with higher pollution in dirty good exporters and lower pollution in dirty good importers. Therefore to isolate the trade-induced composition effect, we must condition on country characteristics. This observation begs three questions - how are we to measure openness, what country characteristics should we use, and how should we condition on these characteristics?

Various measures of "openness" exist. We need a measure with both time-series variation and a wide cross-country coverage. In our theory a lowering of trade frictions brings domestic prices closer to world prices and it does not matter whether this occurs because of a fall in transport and communication costs or (apart from revenue effects) because of a GATT inspired reduction in trade restrictions.[19] But since we do not observe movements in β directly we must make use of an observable consequence of heightened integration: increases in a country's trade intensity ratio (defined as the ratio of exports plus imports to GDP valued at world prices). We formalize this link below.

Proposition 5 *If preferences over consumption goods are homothetic, trade intensity rises as β approaches 1.*

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

[19]See however section III.E on the tariff-substitution effect in a large open economy.

Proof: See Appendix A.

Proposition 5 links unobservable trade frictions with observable trade intensity. Lower trade frictions means greater trade intensity, regardless of a country's comparative advantage. Therefore, in our empirical application we replace unobservable trade frictions with observable trade intensity.[20]

To address our second question, interpret the hat notation in equation (23) as describing small differences across countries. With this interpretation, (23) links differences in autarky relative prices across countries to differences in their relative factor abundance and real income levels. If we take the rest of the world as our small country's partner in this exercise, then the strength and direction of country i's comparative advantage will depend on its capital abundance relative to a world average (denoted by κ_i), and its real income relative to a world average (denoted by ι_i). While other factors play a role in determining comparative advantage, capital abundance and real income are the key country characteristics within our model.

Finally, to condition on these characteristics we let Ψ be a function measuring the partial effect of an increase in trade intensity on pollution. Our theory tells us that we can write $\Psi = \Psi(\kappa_i, \iota_i)$, but does not give us much more guidance in this regard. The interaction between factor abundance and pollution haven motives depends quite delicately on elasticities of substitution, factor shares, and (unknown) third derivative properties of our more basic functions. This is apparent from (23) because the elasticities in this expression are functions of prices, incomes and trade frictions. Consequently, we adopt a flexible approach to capturing these influences by adopting a 2nd order Taylor series approximation to Ψ in our empirical work. That is, we

employ

$$\Psi_i \cong \psi_0 + \psi_1 \kappa_i + \psi_2 \kappa_i^2 + \psi_3 \iota_i + \psi_4 \iota_i^2 + \psi_5 \kappa_i \iota_i \tag{24}$$

and then interact this measure with trade intensity to capture the trade-induced composition effect.

This method has several advantages. It allows the impact of further openness on pollution to depend on country characteristics. It does not dictate whether one or both motives are present in the data or how they interact. And we can evaluate Ψ using our estimates to provide some simple reality checks. For example, does the pollution demand curve shift right for some countries and not for others? (i.e. does Ψ_i vary in sign depending on country characteristics). For which countries does it shift right? Are these countries poor countries as predicted by the pollution haven hypothesis, or are they capital abundant countries as predicted by the factor abundance hypothesis? Finally, the formulation is a relatively parsimonious and reasonably flexible method for estimating an unknown nonlinear function.

II. 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 (subsection A) and address the links between theory and our estimating equation (subsection B).

A. 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 as well as "open" and "closed" economies. An almost perfect choice for this study is sulfur dioxide.

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[20]If trade frictions are not exogenous, but are endogenously determined along with pollution policy, then our proxy (trade intensity) may be correlated with unmeasured determinants of pollution policy. In section III.E we discuss the likely implications of such a link between trade and pollution policy.

Sulfur dioxide is a noxious gas produced by the burning of fossil fuels. Natural sources include volcanoes, decaying organic matter and sea spray. Anthropogenic sources are thought to be responsible for somewhere between one-third to one-half of all emissions (United Nations Environment Programme (1991), Kraushaar and Ristinen (1998)). SO_2 is primarily emitted as either a direct or indirect product of goods production and is not strongly linked to automobile use. Because energy intensive industries are also typically capital intensive, a reasonable proxy for dirty SO_2 creating activities may be physical capital-intensive production processes. Readily available although costly methods for the control of emissions exist and their efficacy is well established. In addition, in many countries SO_2 emissions have been actively regulated for some time.

The Global Environment Monitoring System (GEMS) has been recording SO_2 concentrations in major urban areas in developed and developing countries since the early 1970s. Our data set consists of 2555 observations from 290 observation sites located in 108 cities representing 43 countries spanning the years 1971-1996. The GEMS network was set up to monitor the concentrations of several pollutants in a cross section of countries using comparable measuring devices.[21] 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. World Health Organization (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.

The GEMS data is comprised of summary statistics for the yearly distribution of concentrations at each site. In this study we use the log of median SO_2 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 SO_2 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 level of the pollutant below zero.

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 along with a frequency distribution of $S0_2$ emissions is given in our Technical Appendix available upon request.

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 meteorological 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 description of data sources and our methods for collection are provided in Appendix B together with a table of means, standard deviations, and units of measurement for the data.

B. The Estimating Equation

In moving from our theoretical model to estimation we face several issues. Here we discuss three: identification, excluded variables, and functional form.

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[21]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.

Identification

The private sector's demand for pollution, written in differential form, is given by (17). The pollution supply curve is given by (18). A problem arises because most measures of the scale of economic activity that shifts pollution demand (for example real GDP or real GDP per person) will be highly or perfectly correlated with real income per capita that shifts pollution supply.

We address this problem by exploiting three different sources of variation in our data. First, we note that changes in the scale of output must have contemporaneous effects on pollution concentrations, whereas pollution policy is likely to respond slowly, if at all, to changes in income levels. Consequently, we use as our proxy for income a one-period lagged, three year moving average of income per capita, but link pollution concentrations to a contemporaneous measure of economic activity. To the extent that there is significant variation over time in activity measures, this source of variation will help in our identification.[22]

Second, the scale of economic activity should be measured by economic activity within a country's borders—i.e. GDP—whereas the income relevant to the technique effect should reflect the income of residents wherever it is earned—i.e. GNP. Therefore, we can exploit the difference between GDP and GNP measures to separate technique from scale effects. While the gap between these two figures is not large for most economies, it is significant for some. This cross-country variation will be useful in separating scale from technique.

Finally, we measure the scale of economic activity, S, at any site by 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. As a result, scale is now measured in intensive form, as is our dependent variable.[23] To explain *concentrations of pollution* we need a measure of scale reflecting the *concentration of economic activity* within the same geographical area. Other possible measures of scale fail this test. Moreover, since we assume pollution policy is determined by national averages for income per capita and the number of exposed individuals, we are in effect fixing the pollution supply curve for all cities within a given country. This "allows" us to employ the within-country variation in scale across cities to separate the influence of scale from that of technique.

Unobservable variables: Fixed or Random Effects?

Several variables relevant to our theory are unobservable. To account for these exclusions we estimate an individual effects model for ϵ_{ijkt} given by:

$$\epsilon_{ijkt} = \xi_t + \theta_{ijk} + \nu_{ijkt} \qquad (25)$$

where ξ_t is a time specific effect, θ_{ijk} is a site-specific effect, and ν_{ijkt} is an idiosyncratic measurement error for observation station i in city j in country k in year t.

Our common-to-world, but time specific effect is included to capture changes in knowledge concerning pollution, changes in the world relative price of dirty goods, and improvements in abatement technologies. While proxies for some of these variables could be constructed, choosing proxies will of course introduce new issues of data quality, coverage, etc. Instead we note that because each of these variables affects all countries in a similar way, a preferred method

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[22]For example, we expect that a significant recession would drive down concentrations (a scale effect) but not lead to a rewriting of pollution control laws (i.e. a technique effect). This source of variation in pollution data has been exploited before. See Chay and Greenstone (1999).

[23]This is admittedly a rough measure of economic activity, and the quality of this proxy may vary systematically with a country's development level. To investigate this concern we have allowed the scale effect to vary across countries divided by income category, by allowing for non-linearities in the response to scale, and by excluding the perhaps most troubling rural observations. Our results are similar to those reported for our simpler specification. For one such sensitivity see Table 2.

may be to treat them as unobservable. For example, a rise in the world price of dirty goods affects all countries in a similar way. Accordingly, we capture these common-to-world excluded variables with a set of unrestricted time dummies.

θ_{ijk} is a site-specific effect representing excluded site (or country-specific) variables such as excluded economic determinants, or excluded meteorological variables. For example, country type T appears in (19) but is virtually unobservable since it relies on both knowledge of the weight governments apply to Greens and Browns in their economy and the share of each in the overall population. Since the panel is relatively short for almost all countries, we take these country type and distribution parameters as fixed over time. As well, there are unmeasured topographical and meteorological features that undoubtedly affect the dissipation of pollution at each site. Finally we allow for an idiosyncratic measurement error ν_{ijkt}. Two sources of this error would be machine error in reading concentrations and human error in calculation or tabulation.

Throughout we present both fixed and random effects estimates for every model. While random effects estimation is in theory more efficient, it is unclear whether excluded country-specific effects subsumed in our error term are uncorrelated with our regressors. And while fixed effects estimation is preferable in just these cases, fixed effects limits the cross-sectional variation we can exploit for separating scale from technique effects.

Functional form

Our model predicts emission levels but our data is on concentrations. Meteorological models mapping emissions from a (single) stack into measured concentrations at a receptor are functions of emission rates, stack height, the distance to the receptor, wind speed, temperature gradients and turbulence. Much of this information is not presently available. In view of these limitations we adopt a linear approximation to measured concentrations by writing concentrations

at site ijk, at time t as:

$$
\begin{aligned}
Z^C_{ijkt} &= X'_{jkt}\alpha + Y'_{ijkt}\gamma + \epsilon_{ijkt} \\
X'_{jkt}\alpha &= \alpha_0 + \alpha_1 \text{SCALE}_{jkt} + \alpha_2 \text{KL}_{kt} \\
&\quad + \alpha_3 \text{INC}_{kt} + \alpha_4 \Psi_{kt} \text{TI}_{kt} \\
\Psi_{kt} &= \psi_0 + \psi_1 \text{REL.KL}_{kt} + \psi_2 \text{REL.KL}^2_{kt} \\
&\quad + \psi_3 \text{REL.INC}_{kt} + \psi_4 \text{REL.INC}^2_{kt} \\
&\quad + \psi_5 \text{REL.KL}_{kt} \text{REL.INC}_{kt} \quad (26)
\end{aligned}
$$

where SCALE is city-specific GDP/km^2, KL is the national capital-to-labor ratio, INC is a one-period-lagged 3 year moving average of GNP/N, TI is the trade intensity (X+M)/GDP, REL.KL is country k's capital-to-labor ratio measured relative to the world average, and REL.INC is country k's real income measured relative to the world average (see Appendix B for further detail). Note that world price and country type variables are captured in (25), and trade intensity has replaced trade frictions in (19) as discussed previously. Y contains site-specific weather variables and site-specific physical characteristics (discussed below), and ϵ_{ijkt} is a site-specific error reflecting unmeasured economic and physical variables. We refer to equation (26) as Model A in our estimations.

Model A follows from our reduced form if we assume linearity in the response to scale, technique and composition variables. This linearity assumption is, however, somewhat at odds with our theory. In theory, the impact of capital accumulation on pollution depends on the techniques of production in place. But when countries differ in income per capita, they will also differ in producer prices and hence their techniques of production. Consequently, the Rybczynski derivatives embedded in (26) will differ across countries. As well, the impact of capital accumulation on the composition of output is not a linear function of KL. Similarly, the impact of income gains on pollution depend on the existing composition of output and hence the existing capital-to-labor ratio and income per capita. To account for these possibilities we amend Model A by adding the squares of income per capita (INC^2_{kt}) and the capital-to-labor ratio (KL^2_{kt}) as well as their cross product ($\text{INC}_{kt}\text{KL}_{kt}$). We refer to this amended

form of (26) as Model B. As a consequence, the impact of factor accumulation can now differ across countries and over time in closer accord with our theory. Finally, we consider a further non-linearity by adding SCALE^2_{kt} to model B. A non-linearity in the impact of scale could arise from non-homotheticities in production or consumption. We refer to this slightly amended model as Model C.

Models A, B, and C differ from those previously estimated in several regards. For example, empirical work within the Environmental Kuznet's curve tradition only employ measures of site-specific attributes and income per capita as regressors, leaving out a role for factor endowments or scale to play independent effects. Grossman and Krueger (1993) and (1995) are the most prominent examples of this approach, but there are many others. Gale and Mendez (1998) add measures of factor endowments to a Kuznet's curve regression, but their (one-year) cross-sectional analysis cannot distinguish between constant-over-time site attributes and scale effects. Empirical work using (constructed) cross-country emission data or emission intensity data has tried to link country characteristics (factor endowments, growth in income, fuel use, etc.) to environmental outcomes, but these studies always fail to condition the impact of openness on country characteristics. For example, see Lucas et al. (1992) and Low and Yeats (1992). As a result, we are not aware of even one study where the impact of trade is conditioned on those country characteristics determining comparative advantage - despite the fact that the trade-induced composition effect should vary across countries according to comparative advantage.

III. Empirical Results

A. Main Results

Table 1 presents the main results from our estimations. We present estimates from Models A, B and C in Table 1 using both random and fixed effects.

Scale, Composition and Technique Effects

Consider our core variables representing scale, composition and technique effects. In all columns of table 1 we find a positive and significant relationship between the scale of economic activity as measured by GDP/km^2 and concentrations. From the bottom of table 1 we see that the coefficient estimates imply a sample-mean elasticity of concentrations to an increase in scale somewhere between 0.1 and 0.4. The scale elasticity estimates increases in magnitude as we move from Model A through to C, but the estimates differ only slightly across random and fixed effects. Since the models are nested, we can test the restrictions imposed in Model A and B via a likelihood ratio (LR) test. It appears there is little gained in moving to the slightly more general Model C from Model B; conversely, the restrictions imposed by Model A are rejected by the data as shown by the significant LR test statistics in columns (1) and (4). These empirical results together with our knowledge of theory suggest that less emphasis be placed on the estimates from Model A.

Next consider the impact of a nation's capital to labor ratio. In all columns of Table 1, we find a positive composition effect arising from an increase in capital to labor ratios. The estimated effect is typically quite large. With the exception of column (1), we find a 1 percent increase in a nation's capital-to-labor ratio, holding scale, income and other determinants constant, leads to perhaps a 1 percent point increase in pollution. Our success in finding a link between factor endowments and pollution may appear surprising given the universal difficulties researchers have had in finding a strong link between factor endowments and trade flows. We would note however that the production side of the HOS model has received some support (see especially Harrigan 1995, 1997), and our model focuses on a highly aggregate relationship between overall pollution intensive output and factor endowments.

The estimates in Table 1 also predict a strong and significantly negative relationship between per capita income levels and concentrations. The elasticity of concentrations to an increase in income is typically quite large and is always

TABLE 1: ALTERNATIVE HYPOTHESES TESTS

Estimation Method	Random Effects			Fixed Effects		
Model Specification	A	B	C	A	B	C
Variable / Column	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	-2.865^c	-3.279^c	-3.311^c	-2.506^c	-4.324^c	-4.299^c
City Econ. Intensity GDP/km^2	0.042^c	0.058^c	0.070^c	0.024^a	0.058^c	0.089^a
(City Econ. Intensity)^2/1000			-0.244			-0.340
Capital Abundance (K/L)	0.102^b	0.293^b	0.286^a	0.165^b	0.461^b	0.437^a
(K/L)^2		0.014	0.013		0.006	0.008
Lagged per-capita Income	-0.982^c	-1.248^c	-1.312^c	-1.326^c	-0.096	-0.228
(Income)^2		0.708^c	0.669^c		0.559^c	0.578^c
$(K/L) \times (I)$		-0.309^c	-0.285^c		-0.381^c	-0.386^c
Trade Intensity TI=(X+M)/GDP	-0.915	-0.488	-0.510	-3.677^c	-3.142^b	-3.216^b
TI$\times$ Rel. K/L	-0.462	-1.952^a	-1.828^a	0.159	-2.252^a	-2.121
TI$\times$(Rel. K/L)^2	0.018	-0.230	-0.248	-0.168	-0.123	-0.176
TI$\times$ Rel. Inc.	0.470	1.056^a	1.011^a	2.128^b	2.687^c	2.614^c
TI$\times$(Rel. Inc.)^2	0.118	-0.308^a	-0.285^a	-0.108	-0.595^b	-0.584^b
TI$\times$(Rel. K/L)$\times$(Rel.Inc.)	-0.165	0.870^c	0.822^c	-0.280	0.900^b	0.924^b
Suburban Dummy	-0.299	-0.435^a	-0.422^a			
Rural Dummy	-0.623	-0.674	-0.631			
Communist Country Dummy	0.312	-0.252	-0.257			
C.C. Dummy $\times$ Income	-0.283	4.569^a	4.641^a	1.170	9.621^b	9.639^b
C.C. Dummy $\times$ (Income)^2		-5.755^b	-5.788^b		-8.931^c	-8.806^b
Average Temperature	-0.055^c	-0.052^c	-0.052^c	-0.060^a	-0.057^a	-0.056^a
Precipitation Variation	3.446	5.860	6.158	8.599	10.810^a	10.716^a
Helsinki Protocol	-0.232^a	-0.092	-0.114	-0.179	0.016	0.016
Observations	2555	2555	2555	2555	2555	2555
Groups	290	290	290	290	290	290
R^2	0.3395	0.3737	0.374	0.2483	0.131	0.1499
Log Likelihood	-2550	-2523	-2522	-3964	-3906	-3905
LR Test / χ^2(df)	55.596^c	1.604		118.42^c	2.035	
Hausman Test / Wald χ^2(df)	65.761^b	15.158	53.789			
Scale Elasticity	0.192^c	0.265^c	0.315^c	0.112^a	0.266^c	0.398^b
Composition Elasticity	0.583^b	0.948^c	0.993^c	0.945^b	1.006^b	0.975^a
Technique Elasticity	-0.905^c	-1.577^c	-1.577^c	-1.222^c	-1.153^b	-1.266^b
Trade Intensity Elasticity	-0.436^c	-0.388^c	-0.394^c	-0.641^c	-0.864^c	-0.882^c

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99%, and 99.9% confidence levels are indicated by superscripts ^{a}, ^{b}, and ^{c} respectively. The dependent variable is the log of the median of SO$_2$ concentrations at each observation site. Model A follows directly from our empirical implementation, while model B allows for additional interaction between capital abundance and income. In addition to model B, model C allows for non-linearity in our scale variable. All model specifications use time fixed effects. Elasticities are evaluated at sample means using the Delta method.

significant. Using the estimates from Table 1, the technique elasticity varies between –0.9 and –1.5. This technique effect seems surprisingly strong, but the result appears to be robust. Alternative specifications (discussed below) lead to somewhat different conclusions, but the elasticity is almost universally estimated to be greater than –1 in magnitude, suggesting a strong policy response to income gains.

The Trade-Induced Composition Effect

Next consider the estimates for the trade-induced composition effect. In all columns we reject the hypothesis that the terms reflecting the trade-induced composition effect are jointly zero.[24] While the sign and significance of some individual coefficients varies across specifications, the results from Model B and Model C in both random and fixed effects are very similar. At the sample mean, the overall elasticity of concentrations to an increase in trade intensity is relatively constant ranging from approximately –0.4 to –0.9. Therefore, for an average country in our sample the trade-induced composition effect is negative. Considering the individual coefficients, it is clear that country characteristics describing both relative income and abundance are important, but it is difficult to evaluate the relative strength of pollution haven and factor abundance motives. We present several methods of evaluation below.

Site-specific and country type considerations

Because income gains may not equally translate into policy responses we note it is important to distinguish between communist and non-communist countries. The communist country interactions with income and income squared in Models B and C suggest that the technique effect is very small or non-existent in communist countries. For example, using the fixed effects results from column (6), we cannot reject

the hypothesis of a zero technique effect in communist countries! In the random effects case in column (3), the technique elasticity is fully one-third of that for our average, non-communist, country.[25] We investigated other country-type effects by including a dummy variable for those years a country was bound by the Helsinki protocol on Acid Rain. Our results indicate this variable has little explanatory power. The results do however indicate that site-specific land use and weather variables have a bearing on concentrations as expected. Higher temperatures both dissipate pollution faster and reduce the need for home heating; precipitation highly concentrated in one season reduces the ability of rain to wash out concentrations.

B. Discussion and Evaluation

While the results in Table 1 appear to be supportive of our theory, it is important to go beyond sign and significance tests to investigate whether the magnitude of these estimates are in some sense plausible. We pursue several of these reality checks below.

To start note that the implied scale, composition, and technique elasticities are not implausibly high, and all are significantly different from zero. Together these elasticities provide some simple reality checks. For example, suppose our average economy experienced neutral technological progress of 1 percent raising both GDP and GNP per person by 1 percent. According to our estimates from Table 1, the positive scale effect from this growth will always be dominated by the negative technique effect.[26] While the estimates differ across columns, in all

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[24]This is in contrast to the case where trade intensity appears alone or is replaced by other measures of "openness". We investigated this issue more fully in Antweiler et al. (1998, table 2, page 29).

[25]The technique elasticity in the random effects case is the much smaller –.50 but is significantly different from zero; the technique elasticity in the fixed effects case is –.062 with a 95 percent confidence interval of [–0.90,0.78].

[26]Holding input use constant (capital, labor and pollution), neutral technological progress raises output in our model. Each unit of pollution is more productive than before, and this via a scale effect argues for more pollution. But since real incomes are now higher, pollution may in fact fall from a technique effect. Whether we have more or less pollution in equilibrium after the shock therefore depends on the relative strength of these two effects.

cases our results indicate neutral technological progress lowers pollution concentrations. Alternatively, when an increase in income and production is fueled entirely by capital accumulation, the picture is far less favorable to the environment. If we assume a share of capital in output of 1/3, then the full impact of capital accumulation working through scale, composition and technique effects is to raise pollution concentrations.[27] While these two exercises are not tests of our theory, the results are reassuringly close to what we may have expected ex ante.

To assess the plausibility of our trade intensity elasticity, we calculated the trade intensity elasticity for all countries in our sample. From Proposition 1 we note that the sign of the trade-induced composition effect should reflect a country's comparative advantage in clean versus dirty goods. Therefore it is not plausible that all countries in the world have negative trade intensity elasticities. 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 present in Figures 2 and 3 below a plot of country-specific elasticities against relative income using estimates from Model B in columns (2) and (5) of Table 1. Although there are more positive elasticities in Figure 2 than 3, in both there is a distribution of elasticities around zero. Our inference is simply that some countries' pollution demand shifts right with a fall in trade frictions and some shift left - *because countries differ in their com-*

FIGURE 2: COUNTRY-SPECIFIC TRADE ELASTICITIES (MODEL B, RANDOM EFFECTS, CORRESPONDING TO TABLE 1 COLUMN 2)
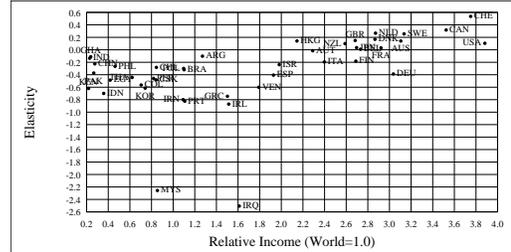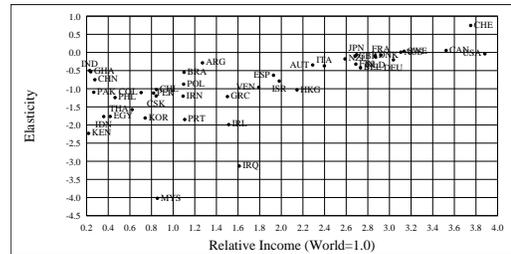

FIGURE 3: COUNTRY-SPECIFIC TRADE ELASTICITIES (MODEL B, FIXED EFFECTS, CORRESPONDING TO TABLE 1 COLUMN 5)

parative advantage.[28] For example, from Figure 2 or 3 we would conclude a small trade liberalization in Canada, all else equal, shifts its pollution demand curve to the right. The inference is that despite Canada's relatively high income, its comparative advantage lies in capital-intensive dirty products. Alternatively, we would conclude a small trade liberalization in India shifts its pollution demand curve to the left. The inference being that despite its relatively low income, its comparative advantage lies in labor intensive and relatively clean goods production. While these two countries estimates may accord well with our intuition, other country specific elasticities are harder to explain (for example why is Malaysia's elasticity so negative and Switzerland's so positive?). Since our country specific

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[27]Take for example the estimates from column (6). Then our estimates indicate that a 1 percent increase in the capital-to-labor ratio raises concentrations by perhaps 1 percent 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 percent increase in the capital-to-labor ratio creates a 1/3 percentage point increase in GDP per capita and GDP/km^2. Therefore, capital accumulation also creates an induced technique effect of approximately $-1.2/3 = -0.4$ and an induced scale effect of perhaps $0.13 = 0.39/3$. Adding the direct composition effect to these estimates suggests that economic growth fueled entirely by capital accumulation raises pollution concentrations.

[28]The random effects implementation in Figure 2 has more positive point elasticities, than the fixed effects in Figure 3, but relatively minor changes in specifications moves the entire set of fixed effects estimates upwards.

estimates do vary across specifications, we caution the reader from drawing too strong an inference from any one of them.

Pollution Haven and Factor Abundance Motives

The second feature of note in Figures 2 and 3 is that the elasticity estimates increase with relative income. Note that if the simple pollution haven hypothesis were literally true and the sole determinant of trade in dirty products, we would expect just the opposite - a strong negative correlation between relative income and the magnitude of our country-specific elasticities. This is because under the pollution haven hypothesis, poor countries specialize in dirty goods and rich countries specialize in clean goods. A small movement towards free trade would shift the pollution demand curve inwards for a rich country and outwards for a poor country. In fact, as shown in the figures, the relationship is definitely non-negative and in fact slightly positive.[29] It appears that if anything, high-income countries have a comparative advantage in dirty capital-intensive products.

In total, while changes in trade intensity seem to matter, the magnitude of the induced change in pollution concentrations appears relatively small. In Figure 2 the vast majority of countries have trade intensity elasticities less than 1 in absolute value; in Figure 3 the majority of countries also satisfy this requirement.

One explanation for these findings is simple: low-income countries typically have both low incomes 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 cost benefits accrue from lax pollution regulation could be largely undone by the relatively

[29]Even excluding the strongly negative elasticities of Maylasia (MYS) and Iraq (IRQ), the relationship is significantly positive in both Figures 2 and 3.

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.

Judging from Figure 2 and 3 it appears that if anything, factor endowment motives are offsetting tighter pollution policy in relatively rich countries. This may explain why other investigations have failed to find a significant relationship between the strictness of pollution regulations and decreased trade in capital-intensive dirty goods. And it may explain why previous researchers have found it quite difficult to find pollution haven effects in the data. 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. But rather, because these two partial theories work against each other, the net result of the potentially very large composition effects predicted by either theory turns out to be rather small in practice.

C. An Environmental Assessment of Freer Trade

Taking factor endowments as fixed, a lowering of transport costs or trade barriers raises the value of domestic output and real income in a small open economy. The value of output and the value of income rise by (approximately) the same percentage, and this creates both scale and technique effects. Using the estimates from either Model B or C in Table 1, the net effect of a 1 percent change in income created by trade is a 0.8-0.9 percent fall in emissions: that is, using (21) we have $\pi_1 - \pi_3 < 0$. The composition effect of trade for our average country is also negative; i.e. from (21) we have $\pi_4 < 0$. Therefore, 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 SO_2 concentrations!

Similar results follow from all of our specifications: the scale elasticity is dominated by the technique elasticity while the trade-induced composition effect of trade is typically small in magnitude.[30] How large a reduction any one country reaps from a fall 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 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.[31] After all the estimated impact of even a large trade liberalization on GDP is small, and when this small increase in GDP is 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 brings knowledge spillovers and hastens technological progress then other calculations must come

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[30]In the Technical Appendix we investigate a 2 equation 2SLS fixed-effects model where our city scale measure and pollution are determined simultaneously. We find a scale elasticity in excess of one, but also a much larger technique elasticity (approaching –2). As a result, our conclusion on their relative magnitude remains unchanged.

[31]Averaging across countries and years the average trade intensity is 41% with a standard deviation of 32% points. A one standard deviation change in trade intensity is then equal to a 79% change in trade intensity from its average value, whereas a 1 standard deviation change in pollution concentrations is equivalent to a 203% change from its average value. Using our fixed effects estimate of the trade intensity elasticity from Table 1 column (6), a 79% increase in trade intensity amounts to a 69% reduction in pollution concentrations, or about one third of a standard deviation of pollution concentration. Using the random effects estimate from column (3) in Table 1, the same one standard deviation change in trade intensity amounts to a change of less than one sixth of the standard deviation in pollution concentration.

into play. Whether these trade-induced changes bring about a net improvement in the environment will depend on their estimated size since 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.

D. Alternative Specifications

The results from Table 1 and Figures 2 and 3 suggest that our approach of dividing the determinants of pollution into scale, technique and composition effects is fruitful. It is however important to investigate whether our results are robust to reasonable changes in specification, time period etc. We have conducted numerous sensitivity tests of our specification and report four alternatives in Table 2 below. Additional results are available in our Technical Appendix available upon request from the authors. In all columns we amend our full model C from Table 1 to include other determinants, investigate other time periods, or adopt more flexible specifications.

In column (1) and (5) we have restricted the time period of our analysis to the years 1976-1991. Before 1976 only a few countries participated and after funding ceased in 1991 country coverage is reduced. To allow for possible data quality and sample selection problems we consider this shorter time period. This shortened period has 489 fewer observations but as shown in columns (1) and (5) the results are similar both in terms of elasticity estimates and significance levels. Our overall conclusions regarding the relative strength of scale versus technique effects remains, as does the muted response to changes in trade intensity.

In column (2) and (6) we investigate the importance of other factor endowments. In our parsimonious model of pollution demand and supply "factor endowments" enter directly only through the inclusion of the capital to labor ratio. Other potential factor endowments were

TABLE 2: SENSITIVITY TESTS

Estimation Method	Random Effects				Fixed Effects			
Model Specification	Time	Factors	FDI	Scale	Time	Factors	FDI	Scale
Variable / Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Intercept	-2.545^c	-3.141^c	-3.650^c	-3.635^c	-1.697	-4.679^c	-4.679^c	-4.345^c
City Econ. Intensity GDP/km^2	0.068^c	0.075^c	0.070^c	0.154^c	0.091^a	0.087^a	0.092^a	0.029
(City Econ. Intensity)^2/1000	-0.054	-0.275	-0.231		-0.254	-0.329	-0.373	
Capital Abundance (K/L)	-0.115	0.289^a	0.439^c	0.279^a	-0.077	0.426^a	0.754^c	0.489^b
(K/L)^2	0.036^b	0.012	-0.002	0.010	0.032	0.008	-0.024	0.006
Lagged per-capita Income	-1.771^c	-1.629^c	-1.451^c	-0.852^a	-3.109^b	-0.428	-0.981	-0.052
(Income)^2	0.585^c	0.717^c	0.660^c	0.611^c	0.512^a	0.757^c	0.563^c	0.564^c
$(K/L) \times (I)$	-0.147^a	-0.276^c	-0.255^c	-0.278^c	-0.041	-0.401^c	-0.297^c	-0.400^c
Trade Intensity TI=(X+M)/GDP	-2.466^c	-0.671	-0.198	-0.501	-7.161^c	-3.333^b	-3.747^c	-2.964^b
TI$\times$ Rel. K/L	0.934	-1.758^a	-2.879^b	-1.890^a	1.699	-2.281^a	-2.737^a	-2.541^a
TI$\times$(Rel. K/L)^2	-0.876^b	-0.252	0.304	-0.142	-1.043^b	-0.131	0.811	-0.112
TI$\times$ Rel. Inc.	1.344^b	1.167^a	1.518^b	1.212^a	4.495^c	3.097^c	2.720^b	2.677^c
TI$\times$(Rel. Inc.)^2	-0.228	-0.309^a	-0.308^a	-0.354^b	-0.742^b	-0.723^c	-0.360	-0.617^b
TI$\times$(Rel. K/L)$\times$(Rel.Inc.)	0.333	0.803^c	0.519	0.784^b	0.164	0.922^b	0.092	0.993^b
Suburban Dummy	-0.284	-0.424^a	-0.445^a	-0.490^b				
Rural Dummy	-0.519	-0.620	-0.655	-0.730^a				
Inward FDI Stock / Capital Stock			0.039				1.234^a	
FDI/K $\times$ poor 30% countries			4.736				6.314	
FDI/K $\times$ rich 30% countries			-0.362				-0.828	
Communist Country Dummy	-0.971^a	-0.326	-0.110	-0.475				
C.C. Dummy $\times$ Income	7.785^c	4.602^a	4.201	5.668^b	16.809^c	11.751^c	10.271^b	9.819^b
C.C. Dummy $\times$ (Income)^2	-8.683^c	-5.683^a	-5.677^a	-7.127^b	-14.13^c	-10.84^c	-8.840^b	-9.039^c
Average Temperature	-0.061^c	-0.056^c	-0.051^c	-0.052^c	-0.072^a	-0.055^a	-0.049	-0.062^a
Precipitation Variation	8.867^a	5.859	7.633	5.882	14.298^b	10.893^a	13.972^b	11.471^a
Hard Coal (per worker)		-0.690				4.217		
Soft Coal (per worker)		2.998^a				4.120		
Helsinki Protocol	-0.242^a	-0.157	-0.092	-0.094	-0.173	-0.054	0.036	0.035
Observations	2066	2555	2525	2555	2066	2555	2525	2555
Groups	274	290	284	290	274	290	284	290
R^2	0.3243	0.3779	0.3684	0.389	0.1677	0.0605	0.1577	0.1337
Log Likelihood	-2030	-2519	-2496	-2512	-2982	-3900	-3858	-3899
Hausman Test / Wald χ^2(df)	94.211^c	55.536	84.269^c	59.331^a				
Scale Elasticity (all/middle)	0.314^c	0.333^c	0.318^c	0.499^c	0.414^a	0.388^a	0.412^b	0.094
Scale Elasticity (poor 30%)				0.643^c				0.355^a
Scale Elasticity (rich 30%)				0.537^c				0.598^c
Composition Elasticity	0.985^c	1.008^c	1.026^c	0.803^c	1.442^b	0.864^a	1.150^b	1.056^b
Technique Elasticity	-1.425^c	-1.740^c	-1.551^c	-1.218^c	-2.220^c	-1.230^b	-1.505^c	-1.204^b
Trade Intensity Elasticity	-0.266^b	-0.351^c	-0.364^b	-0.292^b	-0.543^b	-0.791^c	-1.189^c	-0.899^c
FDI Elasticity (poor 30%)			0.091				0.143	
FDI Elasticity (middle)			0.004				0.121^a	
FDI Elasticity (rich 30%)			-0.039				0.049	

Note: No standard errors or t-statistics are shown, but significance at the 95% and 99%, and 99.9% confidence levels are indicated by superscripts ^{a}, ^{b}, and ^{c} respectively. The dependent variable is the log of the median of SO_2 concentrations at each observation site. All model specifications use time fixed effects. Elasticities are evaluated at sample means using the Delta method. Model "Time" only includes the years 1976-1991 of the primary GEMS phase; model "Factors" introduces factor endowment related variables; and model "FDI" allows for an an inward foreign direct investment stock relative to the overall capital stock, interacted with income.

excluded because while they are undoubtedly relevant to income levels, there is little reason to believe that they have an *independent* effect on either the demand for a clean environment or the derived demand for pollution emissions. Local abundance in either clean or dirty fuels may however affect emissions. We investigate this possibility by adding in columns (2) and (6) country specific measures of hard and soft coal deposits per worker. Overall the results support our earlier conclusions.

While a greater endowment of high sulfur soft coal leads to more concentrations at least in the random effects implementation in column (2), this effect disappears in the fixed effects estimation in column (6). These results are not surprising: an abundance of soft coal means that countries like China will have higher concentrations all else equal, but since mineral endowments have very little time series variation they will be well captured by country fixed effects. Consequently, while abundance of high sulfur coal surely adds to emissions, its explicit inclusion has very little effect on our results.

In columns (3) and (6) we investigate the impact foreign direct investment may have on our results. If multinational corporations have common production methods in both developed and developing countries for engineering, quality control or other reasons, then the pollution intensity of their production will be determined by the income per capita of the source country. As a result, a larger multinational presence in a poor country may mean it is cleaner, all else equal. There is however an alternative hypothesis working in the other direction. If multinationals locate in poor country because of their lax environmental protection, then we may instead find a positive relationship between FDI and pollution. To investigate this issue we have calculated for each year and country in our sample the ratio of its inward stock of FDI to its overall capital stock.[32] We refer to this as FDI

intensity: it measures the share of the domestic capital stock that may have cleaner than expected techniques of production. We then interact this measure with a categorical variable representing a country's income per capita to allow the multinational effect to differ across rich and poor countries. The results from this exercise are mixed. In the fixed effects estimation, there is a slight positive relationship between FDI and concentrations for poor, middle income, and rich countries. Only the middle-income relationship is statistically significant. Moreover, the coefficient estimates imply that a 10 percent point increase in the *ratio* of the FDI stock to K stock would raise concentrations by about 1 percent. This is a small effect on pollution concentrations arising from a very large change in FDI. In the random effects estimation, none of the coefficients are significantly different from zero. Overall, we find little relationship between the extent of FDI in an economy (even a poor one) and its pollution level. Again our elasticity estimates are only changed slightly from our earlier specification.

Finally, in columns (4) and (8) we investigate whether our scale effect differs significantly across countries categorized by income per capita levels. If there were important non-homotheticities in production or consumption, or if our method of constructing scale was more appropriate for some income categories than others, this may show up when we allow for disaggregation. The results in column (4) indicate that while separate estimation of scale across income categories tends to raise the overall elasticity estimates to approximately 0.5 or 0.6, the results are very similar to those presented earlier. In column (8) we find similar results for the poor and rich categories, but the middle-income group has a much lower elasticity and it is not precisely estimated. The middle-income group results may be a consequence of the exclusive reliance of fixed effects on the (now smaller) within-group variation for estimation. Despite these caveats, the elasticity estimates although

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[32]In theory we may want to distinguish between acquisitions of brownfields, capacity expansions, and greenfield investments because greenfield investors are perhaps more likely to bring their own plant-specific technology to the for-

eign country.

different across classes are not significantly different from each other.[33]

E. Alternative Theories: Tariff Substitution and Distributional Motives

In our framework, governments use pollution policy only to target pollution, and not for other purposes, such as to influence the terms of trade or to redistribute income. As a result, the pollution tax is always equal to effective marginal damage, and changes in openness affect our pollution supply curve only through its impact on real income and relative prices. More generally, pollution policy and openness may be linked through other channels if governments use pollution policy for other purposes. To examine this possibility further we need to specify the potential theoretical links involved and then ask what variation in the data such a link would create. There are (at least) two reasons why trade and environmental policies may be linked. Each of these links is probably deserving of a paper-length treatment of both theory and further empirical work, but here our goal is to merely sketch two possibilities and identify their probable impact on our empirical results.

Tariff Substitution

The first link arises from market power. If countries were large and had complete discretion in setting both trade and pollution policy, then both instruments would be targeted: the tariff would be set at its optimal level according to the inverse elasticity rule, and the pollution tax would equal effective marginal damage as in our small open economy case. But if tariff choices are constrained by international agreements, then governments may find it useful to substitute environmental policy for trade policy.

We will refer to this as the tariff substitution motive. To proceed further consider the optimal pollution tax for a large open economy:

$$\tau = T\phi(p, I) + pE_p^* \left(t - \frac{1}{\varepsilon^*} \right) \left| \frac{dp/d\tau}{dz/d\tau} \right| \quad (27)$$

where ε^* is the elasticity of foreign export supply, E_p^* is the price derivative of foreign export supply, and t is the ad valorem tariff. To highlight the tariff substitution motive, rewrite (27) to obtain the gap between the pollution tax and effective marginal damage:

$$\tau - T\phi(p, I) = pE_p^* \left(t - \frac{1}{\varepsilon^*} \right) \left| \frac{dp/d\tau}{dz/d\tau} \right| \quad (28)$$

This gap reflects the tariff substitution motive. Consider first a dirty good importer. When the tariff is set at its optimal level, the right hand side of (28) is zero: each instrument is targeted and there is no tariff substitution motive. If the tariff is constrained to be below its optimal level, then (28) is negative and a dirty good importer sets the pollution tax below marginal damage to substitute for the tariff. Increased openness therefore induces a loosening of pollution policy that was not accounted for in our empirical work.[34] For a dirty good exporter, a similar argument works in reverse: as trade restrictions are reduced below their optimal level, there is an incentive to tighten pollution policy since pollution taxes can be used as a substitute for an export tax. Increased openness in this case leads to a tightening of pollution policy not accounted for in the empirical work.

The Redistribution Motive

Even if countries are small in world markets, governments may adjust pollution taxes to try to undo the redistribution of income caused

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[33]In our random effects implementation we can go further and divide the components of our scale measure into population density and contemporaneous GDP/N. Doing so yields an elasticity of concentrations to population density of 0.57; an elasticity with respect to contemporaneous GDP/N of 0.25; and an overall scale elasticity of 0.65. We cannot reject our restriction that both population density and contemporaneous GDP/N share the same elasticity.

[34]We know that the gap is zero when tariffs are optimal and is negative when tariffs are zero, so "on average" we expect an increase in openness to widen the gap. However it should be noted that since the right hand side of (28) includes the elasticity of foreign export supply, world prices, etc., the gap between τ and marginal damage may not increase monotonically as tariffs fall.

by increased openness. We refer to this as the redistributive motive. To illustrate this motive, retain our small open economy framework, but now assume Greens and Browns differ in factor ownership with Browns having greater capital per person than Greens. And for simplicity let $u(I) = \ln(I)$. Then given the government's weight λ on Greens, the pollution tax will be used both to target pollution and also to influence the income distribution. This again yields a gap between the pollution tax and effective marginal damage:

$$\tau - T\phi(p, I) = \frac{\lambda - s}{s(1-s)}G\left|\frac{ds/d\tau}{dz/d\tau}\right| \quad (29)$$

where s is the share of Greens in national income. Note that if the weight given to Greens exceeds their current share of national income, then the pollution tax is higher than marginal damage. This is because higher pollution taxes lower the producer price of X and raise the real return to labor. Alternatively, if the weight given to Browns is greater than their current income share, the right hand side of (29) is negative: the pollution tax is set below marginal damage to raise the real return to capital.

Consider the effects of increased openness starting from the position where $\lambda = s$. In this case, the pollution tax in a dirty-good exporting country rises above marginal damage to compensate for the Greens' loss in income.[35] Increased openness hurts workers in this case, and the government cushions the blow by tightening the pollution tax to raise wages. For a dirty good importer, the result is reversed: increased openness leads to a loosening of pollution policy to compensate for Browns' loss in income.

Implications of the Theories

Each theory adds a country-specific unmeasured factor to our simpler determinants of pollution. The factor is a country-type effect, and

[35]Let $\Gamma = \tau - T\phi(p, I)$. Then, evaluating at $\lambda = s$, we have $d\Gamma/d\beta = -s_\beta G|s_\tau|/[|z_\tau| s(1-s)] > 0$, since $s_\beta < 0$ (an increase in openness reduces workers' share of income).

it is relevant to both a country's degree of openness and its pollution supply curve. In the large-country case, the unmeasured country type is described by its trade pattern and market power; and in the redistributive theory by its preferred and actual income distribution.

The impact these country-type effects have on our empirical results depends on whether they are time varying. If the country differences are simple level effects and do not vary over time, then our fixed effects implementation is appropriate even if country type is correlated with other right hand side regressors. If country type is uncorrelated with the right hand side variables, then our random effects estimation is more efficient and still unbiased. On average, countries of different types would have different pollution levels, but they would respond similarly to changes in openness, scale, etc. Given the panel is quite short for many countries, this constant-over-time country type assumption may be appropriate.

If these country-type effects are time varying, then they will be correlated with our measure of openness. As a result, our results concerning the effects of further openness and income on pollution may be undermined. To assess whether these motives could be responsible for our results, consider what is left out by our simpler specification. Start with tariff substitution. When tariffs are reduced and openness rises, tariff substitution creates an unaccounted-for upward shift in pollution supply for a dirty-good exporter. This leads to *less* pollution than our model would predict. Alternatively, tariff substitution produces an unaccounted-for downward shift in pollution supply for a dirty good importer. In this case, tariff substitution leads to *more* pollution than our model would predict. In both cases, unaccounted-for shifts in supply work against the shift in pollution demand created by further openness. Similarly, the redistributive motive shifts the pollution supply curve up for a dirty good exporter and down for a dirty good importer in response to increased openness. Again we find that this additional potential determinant of pollution tends to dampen the composition effect created by further openness.

Could tariff substitution or redistribution motives be responsible for the large technique effects we find? Both of these alternative theories lead to an unmeasured positive relationship between pollution and openness for some countries. Therefore, it is difficult to see how the omission of either of these two additional determinants would manifest itself in a stronger measured negative relationship between income and pollution.

These two alternative theories do, however, suggest a smaller (than we would otherwise predict) change in the composition of output created by a fall in trade frictions. As such, another interpretation of our findings of a small trade-induced composition effect is that governments may be simultaneously dampening the impact of increased openness on pollution with compensating changes in pollution taxes. To disentangle the additional shifts in pollution supply suggested by either theory from the other effects in our data would require us to obtain information on changes in both tariff levels and pollution regulations over time for many countries in our sample; or employ knowledge about the preferred and actual income distribution in many countries over time. But good cross-country and time series data on pollution regulations and trade protection are unavailable, and the preferred income distribution is unobservable. These two alternative theories are perhaps best examined within a single country context where data on regulations, tariffs, and income distribution is available.[36]

IV. Conclusions

This paper investigates how openness to trading opportunities affects pollution concentrations. We started with a theoretical specification highlighting scale, technique and composi-

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[36]We discuss here the extreme case where pollution policy is the only available instrument. There are many other instruments (such as production subsidies), which are a better substitute for a tariff; and similarly there are many other instruments (such as income transfers), which can redistribute income. To the extent that these other instruments are available, then the dampening shift in pollution supply that we find below will be less relevant.

tion 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 and Linkins (1996)].

Our work is distinguished by the endogeniety of pollution policy and the close connection we have tried to draw between theory and empirical estimation. While it represents a useful first step towards answering our title's question, it is clearly not the last. The benefits of our approach are transparency, simplicity, and explicitness. We have presented an explicit model of trade and pollution and we have moved from theory to empirical estimation in a transparent manner. Transparency immediately leads to suggestions for extension along both theoretical and empirical lines. Simplicity means additional questions can be addressed within our framework. And the benefit of presenting an explicit pollution demand-and-supply model is that researchers should now be drawn to deeper questions concerning endogeniety, omitted variables, and sample selection. We view this paper's attempt at integrating theory with empirical work as its major contribution to ongoing research in this area.

Several extensions seem natural. One cost of reduced form estimation is that structural parameters remain hidden. Reduced form estimation was essentially forced on us by the lack of data

on regulations in many developing countries. If we adopt similar methods but restrict the sample to industrialized countries, we could then employ measures of pollution stringency as proxies for pollution regulations. With data on both the quantity and "price" of pollution, the identification of structural parameters seems possible. A shift to a narrower set of countries with more detailed data may also allow us to examine the tariff-substitution and redistributive motives we discussed, but did not estimate, here. Finally, our method for adding up scale, composition and technique effects could be enhanced by direct estimates of the income gains brought about by trade liberalization, and improved by explicit consideration of foreign direct investment and technology transfer.

As with any empirical exercise some questions remain unanswered, but overall our estimates 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 a 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 percent, pollution concentrations fall by approximately 1 percent. Putting this calculation together with our earlier evidence on composition effects yields a somewhat surprising conclusion with regard to sulfur dioxide: freer trade is good for the environment.

APPENDIX

A. Proof of Propostions

Proof of Proposition 1. Use (17)-(18), and hold T, S, I, K/L and p^w constant:

$$\hat{z} = [(1+a)\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}]\hat{\beta} - [a\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}]\hat{\tau}$$
$$= \left[\varepsilon_{\varphi,p} + \left(a\varepsilon_{\varphi,p} + \varepsilon_{e,p/\tau}\right)(1 - \varepsilon_{MD,p})\right]\hat{\beta}$$

Using Roy's identity, we can show that $\varepsilon_{MD,p}$ is equal to the share of x in consumption (note that when calculating this elasticity, real income I is held constant, and so we obtain a pure substitution effect). Hence $\varepsilon_{MD,p} < 1$, and z rises as β rises. For a dirty good exporter, increased openness corresponds to an increase in β, and hence all else equal, a reduction in trade frictions raises pollution. For a dirty good importer, a reduction in trade frictions lowers β, and pollution falls.

Proof of Proposition 2. Note $z = -R_\tau$ (where $R_\tau = -eR_{p^N}$ and $R_{\tau\tau} > 0$). Then:

$$dz = -\left[R_{\tau\tau}d\tau + p^w(1-\theta)R_{\tau p^N}d\beta\right]$$
$$= R_{\tau\tau}\left[p^w \left.\frac{d\tau}{dp}\right|_z d\beta - d\tau\right]$$

where the last step follows from differentiating $z = -R_\tau$, holding z constant. Next. eliminate $d\tau$ by differentiating (10) noting that $I = G/(N\rho)$ and that $dG = p^w(1-\theta)R_{p^N}d\beta + \tau dz$. Rearranging and converting to elasticity form yields:

$$\frac{dz}{d\beta} = \left[\left.\frac{p}{\tau}\frac{d\tau}{dp}\right|_z - \varepsilon_{MD,p} + \varepsilon_{MD,I}\frac{pM}{G}\right]/H$$

where M is imports of X and H is a positive expression. From the proof of Proposition 1, $\varepsilon_{MD,p} < 1$. But $(p/\tau)(d\tau/dp)|_z > 1$ since $z = ex$ and e is decreasing in τ/p. (An increase in p raises x, and so to keep z constant, we need τ/p to rise.) Hence if $M > 0$, then $dz/d\beta > 0$ and so increased openness reduces pollution for a dirty good importer (β falls). For a dirty good exporter, $M < 0$ and β rises when openness rises. From the proof of Proposition 1, $\varepsilon_{MD,p}$ is the share of X in consumption, and so with $\varepsilon_{MD,I} \leq 1$, we have

$$\frac{dz}{d\beta} > \left[\left.\frac{p}{\tau}\frac{d\tau}{dp}\right|_z - \frac{px}{G}\right]/H > 0$$

where $px/G < 1$ is the share of X in output at domestic prices. So pollution rises for a dirty good exporter if $\varepsilon_{MD,I} \leq 1$. Finally, if $\varepsilon_{MD,I}$ is sufficiently large, the sign of $dz/d\beta$ is reversed for a dirty good exporter and pollution falls as openness rises.

Proof of Proposition 3. For a given p and I, Home's relative demand $RD(p)$ is fixed. For given p and I, the unit input coefficients given in (6) are fixed, and hence χ approaches infinity as κ rises. Consequently, there exists a $\underline{\kappa}$ such that for $\kappa > \underline{\kappa}$, χ exceeds relative demand, and Home exports X. The increase in pollution via the trade-induced composition effect follows from Prop. 1.

Proof of Proposition 4. The relative producer price of X is $p^N < p(1 - \theta) - \tau e(1)$ where $e(1) > 0$. Because $\varepsilon_{MD,I} > \varepsilon > 0$, τ increases without bound as income rises given (18). Moreover, θ rises from (4), and hence there exists some I for which p^N falls to 0, in which case X output 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 from the trade-induced composition effect follows from Prop.1.

Proof of Proposition 5. Define trade intensity as the value of exports plus imports at world prices (excluding transportation services). Using the trade balance constraint,

$$\text{TI} = 2p^w \frac{|M_x|}{p^w(1 - \theta)x + y}$$

where M_x is imports of X. Consider first an importer of X ($M_x > 0$). Let $G^w = p^w(1 - \theta)x + y$, and $G = \beta p^w(1 - \theta)x + y$. By homotheticity, we can write the demand for X as $D^x = h(p)G$. Letting $\delta^x = p^w D^x/G^w$, and $\varphi = p^w(1 - \theta)x/G^w$, we have TI$=2(\delta^x - \varphi)$. With some rearranging, we can write:

$$\delta^x = p^w h \left(1 + (\beta - 1)\varphi\right)$$

Then

$$\frac{1}{2}\frac{\partial \text{TI}}{\partial \beta} = \frac{\partial \delta^x}{\partial \beta} - \frac{\partial \varphi}{\partial \beta}$$

$$= \frac{(p^w)^2}{G^w}\left[\left.\frac{\partial D^x}{\partial p}\right|_u - \frac{\partial D^x}{\partial G}M_x\right] + \left[p^w h(\beta - 1) - 1\right]\varphi_\beta < 0$$

where we have used the Slutsky decomposition. Note that the substitution effect in demand is negative ($\partial D^x/\partial p|_u < 0$) and the income effect ($\partial D^x/\partial G$) is positive, so the bracketed term involving demand changes is negative. As well $p^w \beta h < 1$ from the consumer's budget constraint, and $\varphi_\beta > 0$ (an increase in β shifts production toward X) and so the last term is negative as well. Thus $\partial \text{TI}/\partial \beta < 0$ for an importer of X. Hence a fall in β (a movement toward 1) increases trade intensity. For an exporter of X, one can proceed most simply by replacing $|p^w M_x|$ with imports of Y, M_y in the definition of trade intensity and following a similar analysis as above to conclude that an increase in β (a movement toward 1) raises trade intensity.

B. Data Set Description

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.

We have chosen to use a logarithmic transformation of the median SO_2 concentration as our dependent variable. The distribution of concentrations is highly-skewed towards zero when viewed on a linear scale. As was pointed out in the WHO (1984) report about the GEMS/AIR project, concentrations are more suitably described by a log-normal distribution with a number of observations concentrated at the measurement threshold of the measurement devices. There is also an ambient level of SO_2 in the air that has natural causes.

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. Many of the other observation stations provided short or discontinuous streams of data while participating in the GEMS/AIR project. 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.

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 program sponsored by the United Nations World Health Organization.[37] 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.

Additional data sources for our regressors include the *Penn World Tables*[38] for macroeconomic data, the *World Investment Report*[39] for inward FDI stock data, the CIESIN *Global Population Distribution Database*[40] for population density data, the World Resources Insti-

titute *World Resources Database*[41] for natural resources and physical endowments, and data from the *Global Historical Climatology Network*[42] (GHCN) for weather conditions at the observation stations. Yet more time series were obtained for tariff and non-tariff trade barriers,[43] and educational attainment.[44]

Summary statistics for the major variables appear in table B-1. Some of the variables warrant further explanation. First, our scale measure of economic activity GDP per square kilometre is calculated by multiplying a country's real per-capita GDP ($/person) with 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.

The capital abundance (K/L) of countries was obtained from the physical capital stock per worker variable in the Penn World Tables. We have adjusted this series for human capital by applying a 0–1 average education index (in which 1 represents 16 years of schooling) obtained from the Barro/Lee data set. Relative capital abundance is obtained by dividing each country's capital abundance by the corresponding world average for the given year, where "world average" is defined by all the countries in the Penn World Tables.

Our income (I) variable is the three-year average of lagged GNP per capita. This addresses two problems. First, contemporaneous income and the level of pollution may be determined simultaneously. Lagged income, however, is exogenous. Second, it is reasonable to assume that income changes translate only slowly into pol-

[37]This package is available from the United States 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.

[38]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. Available in revision 5.6 from the Center for International Comparisons at the University of Pennsylvania at http://pwt.econ.upenn.edu/.

[39]United Nations Centre on Transnational Corporations, 1992 and 1999 volumes.

[40]This data set from the Consortium for International Earth Science Information Network (CIESIN) is only available for 1990. 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.

[41]*World Resources 1998-1999: A Guide to the Global Environment*, Oxford University Press, Oxford: 1998.

[42]Information is available on monthly average temperatures, monthly precipitation, and atmospheric pressure. 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/.

[43]See Sachs and Warner (1995).

[44]These figures were obtained from Robert J. Barro and Jong-Wha Lee 1994 study, available from the NBER web site at http://www.nber.org/pub/barro.lee/ZIP/.

TABLE B-1: SUMMARY STATISTICS

Variable	Dimension	Obs.	Mean	Std.Dev.	Min.	Max.
Log of SO2	$\log_{10}$(ppm)	2555	-2.112	0.481	-3.000	-0.939
City Economic Intensity	\$m per km^2	2555	0.790	0.878	0.010	5.934
GDP per capita (current)	\$10k	2555	1.478	0.862	0.109	2.718
Population Density	1000p/km^2	2555	0.063	0.055	0.001	0.276
Capital Abundance (adjusted)	\$10k/worker	2555	5.612	2.497	0.829	17.189
Capital Abundance (unadjusted)	\$10k/worker	2555	3.207	1.763	0.130	7.750
Education Attainment	0-1 range	2555	0.540	0.226	0.088	0.799
GNP per capita, 3yr avg.	\$10k	2555	1.396	0.815	0.111	2.635
Communist Country	[—]	2555	0.125	0.331	0.000	1.000
C.C. $\times$ Income	\$10k	319	0.302	0.208	0.127	0.716
Trade Intensity (X+M)/GDP	[—]	2555	0.409	0.322	0.088	2.617
Relative (K/L) (adj.)	World=1.00	2555	1.357	0.605	0.203	4.174
Relative Income	World=1.00	2555	2.500	1.392	0.221	4.138
Inward FDI Stock / Capital Stock	[—]	2525	0.106	0.250	0.001	2.193
Avg. Temperature	°C	2555	14.689	5.600	2.617	28.967
Precipitation Coeff. of Var.	[—]	2555	0.011	0.006	0.001	0.054
Hard Coal Reserves	GJoule/worker	2555	0.040	0.043	0.000	0.146
Soft Coal Reserves	GJoule/worker	2555	0.038	0.052	0.000	0.348

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

icy changes. We therefore smooth out some of the variation introduced through business cycles and include three years of data. (We also experimented with longer lags, without much effect on our results.) More concretely, for a given year t we compute $I_t = (y_{t-1} + y_{t-2} + y_{t-3})/3$. Relative income is constructed in the same fashion as our relative capital abundance measure. GNP figures were obtained by adjusting GDP figures with a GNP/GDP correction factor obtained from the International Monetary Fund's *International Financial Statistics*. However, such correction factors were unavailable for the former Czechoslovakia, Egypt, Hong Kong, Iraq, Pery, Poland, and the former Yugoslavia. Unadjusted GDP figures were used in these cases.

The data on foreign direct investment were obtained as percentages of the stock of inward FDI relative to GDP, and interpolated where necessary. Then these figures were divided by GDP to capital stock ratios obtained from the Penn World Tables in order to obtain the percentage of inward FDI stock relative to a country's entire capital stock.

The suburban and rural location type dummy variables are from the oiriginal GEMS/AIR dataset. The third (default) location type is central city. Our trade intensity measure is calculated as the sum of exports and imports expressed as a percentage of gross domestic product. The communist country dummy used in our study identifies the following countries: China, Czechoslovakia, Poland, and Yugoslavia. The country dummy for the Helsinki Protocol identifies Austria, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, Finland, France, Germany, Hungary, Italy, Luxembourg, The Netherlands, Norway, and Switzerland, in the years after 1985.

For the purpose of calculating sample-mean elasticities we have used averages of the relevant variables calculated as follows. An average country value for variable X is calculated by first averaging X's values over time for each country, and then averaging across countries. This procedure gives equal weight to all countries.

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