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NORTH-SOUTH TRADE AND THE ENVIRONMENT*

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A simple static model of North-South trade is developed to examine linkages between national income, pollution, and international trade. Two countries produce a continuum of goods, each differing in pollution intensity. We show that the higher income country chooses stronger environmental protection, and specializes in relatively clean goods. By isolating the scale, composition, and technique effects of international trade on pollution, we show that free trade increases world pollution; an increase in the rich North's production possibilities increases pollution, while similar growth in the poor South lowers pollution; and unilateral transfers from North to South reduce worldwide pollution.

I. INTRODUCTION

One of the most interesting developments in trade policy in recent years has been the emergence of trade liberalization as an environmental issue.[1] In addition to facing traditional protectionist pressures, recent initiatives such as the North American Free Trade Agreement and the Uruguay Round of GATT negotiations have been questioned on the grounds that they might increase pollution. This has led to much debate about the environmental consequences of free trade.

Proponents of freer trade argue that environmental quality is a normal good, and hence trade-induced income gains should create political demands for tougher environmental standards. Tougher standards should in turn bring forth cleaner *techniques* of production. Skeptics, however, point out that if production methods do not change, then pollution must rise as trade increases the *scale* of economic activity. Moreover, if environmental quality is a normal good, then less developed countries will adopt relatively low environmental standards. As a result, because of asymmetries in the world distribution of income, free trade may affect the *composition* of national output with many developing countries turning toward relatively pollution-intensive activities. Grossman and Krueger [1991] and others have recently begun to investigate the

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1. See Anderson and Blackhurst [1992] and Dean [1992] for useful surveys of the literature on trade and the environment.

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empirical significance of each of these effects, but the issue has received relatively little attention in the theoretical literature.

This paper takes a first step toward clarifying the theoretical issues by developing a simple static two-country general equilibrium model in which income-induced differences in environmental policy create incentives to trade. Using this framework, we first define the scale, technique, and composition effects,[2] and link their magnitudes to tastes, technologies, and endowments. We then use this decomposition to examine how pollution levels are affected by trade liberalization, exogenous increases in production capacity (scale-induced increases in income), and international transfers (redistributions of world income). We emphasize income effects because they determine the strength of the technique effect mentioned above, are tied to the scale of economic activity, and can determine how free trade affects the composition of national outputs and overall pollution levels.

Since the primary objective of the paper is to investigate factors determining the level and international incidence of pollution, we focus on positive rather than normative issues. As well, we simplify the analysis by assuming that the damage caused by pollution is confined to the country of emission.[3] As a consequence, it is perhaps wise to remind the reader at the outset that increases in pollution levels should *not* be viewed as equivalent to decreases in welfare. In fact, trade is always welfare-improving in our model, even when it raises pollution levels.

Our results indicate that increases in economic activity per se need not lower environmental quality because income effects can lead to the adoption of cleaner techniques of production. However, this conclusion must be tempered when we move to an open economy: we find that openness to international markets fundamentally alters the way in which income effects determine pollution levels. For example, in our model, economic growth[4] in autarky has no effect on pollution levels, but economic growth in a trading environment can raise pollution levels. Moreover, the distribution of growth across countries matters: growth in the rich North may

2. The "scale, technique, and composition effect" terminology has been employed by several authors, including Grossman and Krueger [1991], but explicit model-based definitions of these effects have yet to be presented.

3. Transboundary pollution is clearly an important issue, but its analysis is left to a companion paper [Copeland and Taylor 1993]. This allows us to abstract from problems of policy failure due to the lack of an international government, and frees us to concentrate on the transmission mechanisms linking trade and pollution.

4. By "growth" we mean the effect of once-for-all increases in technological capabilities or endowments.

increase pollution, while growth in the poor South lowers pollution. Freer trade, like growth, raises real incomes, but it also changes the composition of national output and hence alters both the incidence and level of pollution across countries. If the pattern of trade-induced specialization is driven only by differences in pollution policy, then aggregate world pollution may rise with trade.

The model that we develop has three key features designed to capture what we feel are the essentials. First, since most of the concern over the effect of international trade on environmental quality is motivated by international differences in pollution policy, we adopt a North-South framework in which there is a large income disparity across countries. To generate this disparity in income, we start with a model where countries differ only in the level of human capital per person.[5] As a result, income-induced differences in the level of pollution taxes are the sole determinant of trade flows. This permits an investigation of whether trade that is motivated by differences in environmental policy is inherently pollution-creating, and the simplicity thereby gained also allows us to decompose any change in pollution levels into scale, technique, and composition effects.

In reality, of course, trade is influenced by many conflicting factors. However, as a first step in understanding the interaction between trade and the environment, it is useful to isolate the impact of environmental standards on the pattern of trade.[6] To make inferences about the actual pattern of trade, one would have to weigh the influences derived from environmental policy against other determinants of trade. Current estimates of environmental control costs are relatively small [Dean 1992]. However, marginal control costs are in many cases higher than average costs, and this suggests that environmental control costs are likely to become an increasingly important influence on trade in the future.

Second, to provide a link between income levels and environmental policy, we assume that benevolent planning authorities in each country set pollution taxes to offset the marginal damage from

5. In Section VII of the paper we examine how differences in population density, country size, and physical carrying capacity of the environment can also affect trade flows.

6. This is a fairly standard methodology. For example, Staiger [1987] uses a similar model to investigate the effect of unionization on the pattern of trade, and assumes that differences in the scope of unionization are all that differentiate countries. Similarly, much of the early literature on increasing returns to scale abstracted from all other incentives to trade.

emissions. This assumption ensures that pollution is optimally provided in both autarky and trade and, moreover, that governments adjust pollution policy in response to changed economic circumstances such as growth or trade. While this may reflect an overly optimistic belief in the capabilities of government policy, it is the simplest way to capture the view that governments are responsive to the preferences of their citizens.

Finally, to capture the effect of differing standards of environmental protection on trade patterns, we adopt a many-good general equilibrium model based on Dornbusch, Fischer, and Samuelson [1977]. By adopting a general equilibrium approach, we ensure that the full impact of environmental policy can be traced through to its ultimate effects on factor markets, incomes, and trade flows. A many-good framework allows us to highlight composition effects. If, as we assume, industries differ in their pollution intensities, then changes in the composition of output arising from free trade will affect both national and world pollution levels.

Several previous studies [Baumol and Oates 1988; Pethig 1976; Siebert et al. 1980; McGuire 1982] have investigated the effects of pollution policy on the pattern of trade. Pethig [1976] extends the two-good Ricardian model to include pollution, and shows that if two countries are identical, except that they exogenously set different emission standards, then the country which allows a higher level of pollution emissions will export the pollution-intensive good. Siebert et al. [1980] and McGuire [1982] extend the analysis to the case of two primary factors. Pollution policy in all of these models, however, is exogenous. By endogenizing policy in the present paper, we explain the pattern of trade as a function of the underlying technology and endowments, rather than as merely reflecting exogenous policy differences. This allows us to examine explicitly the role that income differences may play in determining the pattern of trade. This issue, which is the subject of much policy debate, has not been addressed in previous formal models.[7]

Recent empirical work in the area is mixed. Grossman and Krueger [1991] examine data on air pollution levels in 43 developed and developing countries and conclude that pollution levels first

7. There is also a literature on optimal choice of pollution policy and trade policy in an open economy (see, for example, Markusen [1975], Baumol and Oates [1988], and Copeland [1994]). The focus of this literature is on the structure of the optimal policy for a single country, whereas in our paper we are concerned with how the choice of policies in two countries interact to determine the pattern of trade. Moreover, this literature has not examined how optimal pollution policy would differ systematically across countries that have different income levels.

rise and then fall with per capita income. Therefore, if trade liberalization raises incomes, it may also lower pollution levels. Low and Yeats [1992, p. 94] find that the share of world trade accounted for by pollution-intensive products has experienced a secular decline from 20.4 percent in 1965 to 15.9 percent in 1988; but the export share of such "dirty" goods has been increasing for many developing countries. In addition, Lucas, Wheeler, and Hettige [1992] find that although many developed countries are experiencing a fall in the pollution intensity of national product, this appears to be due to a change in the composition of output and *not* a movement toward cleaner production methods. These last two results suggest that international trade may be serving as a vehicle for dirty industry migration to less developed countries. While our model is highly stylized and abstracts from other important determinants of trade, it provides a useful starting point from which to interpret the earlier empirical work.

It is important, however, to recognize the limitations of our analysis. For example, openness to international markets may mean less developed countries gain access to better pollution abatement technology and to international capital markets. Our analysis limits the effects of openness to those arising from goods trade. As well, our conclusions follow from a decidedly stark model. While we are able to derive unambiguous answers to many questions and clearly identify the forces at work, there is much scope for future work aimed at relaxing some of our assumptions.

The remainder of the paper is organized as follows. Section II sets out our assumptions on preferences and technologies. A simple diagrammatic framework to analyze the equilibrium is developed in Section III. Section IV explores the relation between international trade and the level of pollution; we also derive the scale, technique, and composition effects at this point. The effects of economic growth and international transfers on pollution are investigated in Sections V and VI. Section VII considers some extensions of the model, and Section VIII concludes.

II. The Model

We consider a world with two countries: the highly developed North and the less developed South. Southern variables are indicated by an asterisk (*). There is a continuum of private consumption goods, indexed by $z \in [0,1]$, and one primary input, effective labor (to be described in more detail below). Pollution is

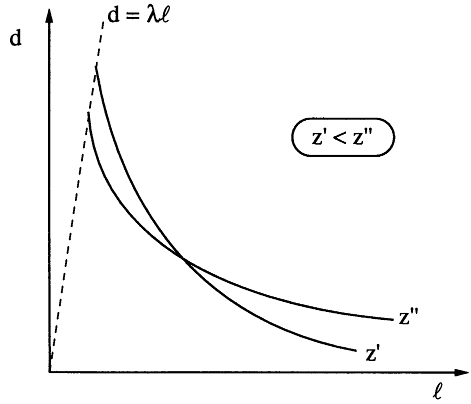

FIGURE I
Unit Isoquants for Two Industries, z' and z''
Industry z'' is more pollution intensive than industry z'.

produced jointly with consumption goods. We assume that the output (y) of good z can be written as a function of pollution discharge (d) and effective labor input (l).[8] To keep the model simple, we adopt the following functional form:

$$(1) \qquad y(d,l;z) = \begin{cases} l^{1-\alpha(z)}d^{\alpha(z)} & \text{if } d \leq \lambda l, \\ 0 & \text{if } d > \lambda l, \end{cases}$$

where $\lambda > 0$ and $\alpha(z)$ is a parameter that varies across goods. We assume that $\alpha(z) \in [\underline{\alpha},\overline{\alpha}]$, with $0 < \underline{\alpha} < \overline{\alpha} < 1$.

Isoquants for two typical goods z' and z'' are illustrated in Figure I. For any given level of output of a good, a firm may choose among a continuum of production techniques, each of which generates different levels of pollution. By moving down and to the right along the isoquant, the firm adopts relatively cleaner technologies by abating pollution at the expense of more labor input. Note that the specification in (1) is analytically equivalent to treating pollution as an input that can be substituted for labor in the production of good z.[9] There is a limit to these substitution

8. This requires that the joint production technology satisfy certain regularity conditions. In the Appendix we show how equation (1) can be derived from a joint production technology.

9. The treatment of pollution as an input has been adopted by several others; see, for example, Pethig [1976], Siebert et al. [1980], and McGuire [1982].

possibilities, however, because output must be bounded above for a given labor input. Hence points above the line $d = \lambda l$ are not feasible.[10]

If firms were unregulated, they would have no incentive to abate pollution and would always choose a point along the line $d = \lambda l$ in Figure I. We assume throughout, however, that governments regulate pollution and that firms chose interior solutions where they engage in at least a small amount of abatement.[11] Consequently, if a pollution tax τ is imposed and w_e is the return to a unit of effective labor, the firm's labor/pollution combination that minimizes costs satisfy

$$\frac{w_e}{\tau} = \frac{1 - \alpha(z)}{\alpha(z)} \frac{d}{l}. \tag{2}$$

An implication of (2) is that the share of pollution charges in the cost of producing good z is always $\alpha(z)$. As a result, we can order the goods in terms of increasing pollution intensity to obtain $\alpha'(z) > 0$.[12] Thus, in Figure I, if $z'' > z'$, the isoquants for good z'' are flatter than those for good z' along any ray through the origin: good z'' is always more pollution intensive than good z'.

The technologies embodied in (1) are available to both countries. The North-South distinction arises only from an assumed higher level of human capital in the North. Each worker in the North has effectiveness $A(h)$, where h is the level of human capital, and $A' > 0$. Each Southern worker has $h^* < h$ units of human capital, and hence supplies less effective labor than a Northern worker. For most of the paper we assume that each country has the same number of workers, L, so that the total supply of effective labor in the North is $A(h)L$, while that in the South is $A(h^*)L$.

Northern and Southern consumers have identical utility functions defined over consumption goods and pollution. To simplify matters, we assume that utility is strongly separable with respect to consumption and pollution, and we follow Dornbusch, Fischer, and Samuelson [1977] in assuming that the share of spending on each good is constant.

10. To see that this assumption puts an upper bound on production for given labor input, note that with $d \leq \lambda l$, we have $y \leq l^{1-\alpha}(\lambda l)^{\alpha} = l\lambda^{\alpha}$. The Appendix describes in more detail how this constraint arises naturally from an underlying abatement technology.

11. If the South's endowment of effective labor is not too small, then an interior solution will always obtain. See the Appendix for further details.

12. For simplicity, we assume that α is *strictly* increasing in z.

To specify how the damage caused by pollution affects utility, recall that we are concerned with pollution which has only localized effects. Suppose that individuals within a country live in identically sized communities, that pollution generated by one community affects only that community, and that sources of pollution are evenly spread throughout a community. Then pollution damage depends on both the pollution generated per individual, and the community's population density. If population density is very low, people are harmed mainly by their own pollution; but as communities get more crowded, individuals are affected by the pollution of others as well, and the harm caused by pollution rises. As well, if we increase population size but hold aggregate pollution and population density fixed (either by increasing the physical size of the country, or by creating another community distant from the others), then the harm caused by a given amount of aggregate pollution falls since each person is exposed to a smaller fraction of the total pollution.

A simple specification satisfying these requirements is given by

$$U = \int_0^1 b(z) \ln [x(z)]\, dz - \frac{\beta(L,\rho)D^\gamma}{\gamma}, \tag{3}$$

where $x(z)$ is consumption of good z, $b(z)$ is the continuum counterpart to the many-commodity budget share, and $\int_0^1 b(z)dz = 1$. The impact of pollution on utility is captured by $\beta(L,\rho)D^\gamma/\gamma$, where D is the total amount of pollution generated by the country where the individual lives, ρ is the community population density, $\partial\beta/\partial L < 0$, $\partial\beta/\partial\rho > 0$, and $\gamma \geq 1$. The assumption on γ ensures that the marginal willingness to pay for pollution reduction is a nondecreasing function of pollution levels.

Since our main objective is to focus on the effects of income-induced differences in pollution policy on the pattern of trade and environmental quality, in most of the paper we consider the case where all countries are identical in size and population density, and differ only in their per capita endowment of human capital. In this case, β is constant across countries, and to economize on notation, we drop the reference to the arguments of β. In Section VII we examine the more general case where L and ρ differ across countries.

III. North-South Trading Equilibrium

A. Exogenous Pollution Taxes

As a first step toward determining the equilibrium, suppose that North and South have imposed pollution taxes of τ and τ^* per unit of discharge. For concreteness, assume that $\tau > \tau^*$ on the basis of North's higher income (we later show when this holds in equilibrium). Then the unit cost functions derived from (1) and (2) can be written as

$$c(w,\tau;h,z) = \kappa(z)\tau^{\alpha(z)}[w/A(h)]^{1-\alpha(z)}, \tag{4}$$

where $\kappa(z) \equiv \alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}$ is an industry-specific constant, and w is the wage rate for raw labor. For given Northern and Southern taxes and wages, good z will be produced in the North if $c(w,\tau;h,z) \leq c(w^*,\tau^*;h^*,z)$; that is, if

$$\omega \equiv \frac{w}{w^*} \leq \frac{A}{A^*}\left(\frac{\tau^*}{\tau}\right)^{\alpha(z)/(1-\alpha(z))} \equiv T(z). \tag{5}$$

Conversely, good z will be produced in the South if $\omega \geq T(z)$. With $\tau > \tau^*$ and $\alpha'(z) > 0$, T must be decreasing in z: because of North's relatively higher pollution taxes, its cost advantage in producing good z declines as pollution charges become a larger fraction of total costs.

For any given relative wage rate, ω, the $T(z)$ locus determines a critical industry $\tilde{z}(\omega)$ such that goods in the interval $[0,\tilde{z})$ are produced at least cost in the North, while goods over $(\tilde{z},1]$ are produced at least cost in the South. That is, with $\tau > \tau^*$, the North produces the least pollution-intensive goods, while the South produces the most pollution-intensive goods.

B. Endogenous Pollution Taxes

To determine τ and τ^*, first consider a representative Northern consumer's problem. All consumers own one unit of labor and receive an equal share of the pollution taxes collected by their government. Each consumer takes as given prices, aggregate pollution (D), and his or her share of national income (I/L). The indirect utility function corresponding to (3) for a representative consumer is given by

(6)
$$V = \int_0^1 b(z) \ln [b(z)]\, dz - \int_0^1 b(z) \ln [p(z)]\, dz + \ln \left(\frac{I}{L}\right) - \frac{\beta D^{\gamma}}{\gamma}.$$

The government's problem is then to choose its pollution tax τ to maximize V taking as given consumer and producer behavior. We also assume that governments treat world prices as given when choosing their environmental policy. This means that governments do not attempt to use pollution policy to manipulate their terms of trade. There are two reasons why we think that this is the most reasonable assumption. First, in many countries pollution policy is set at the local and state or provincial level, while international trade policy is set by national governments. Any individual local regulator is unlikely to perceive significant international market power. Second, Article XX of the General Agreement on Tariffs and Trade (GATT) requires that countries abstain from using domestic health or environmental policies as disguised trade barriers. Since we wish to focus on the pattern of trade, and not on strategic trade policy, we assume that governments honor their GATT commitments.

Maximizing indirect utility with respect to τ, treating $p(z)$ as given, yields

(7)
$$\tau = -LV_D/V_I = \beta D^{\gamma-1} I,$$

using (3). The government simply sets the pollution tax equal to the marginal damage caused by pollution emissions. Similarly, South's tax is given by $\tau^* = \beta D^{*\gamma-1} I^*$. Pollution taxes are increasing in income since environmental quality is a normal good, and nondecreasing in the aggregate pollution level since the marginal rate of substitution between consumption and pollution is nondecreasing.

We now replace the $T(\cdot)$ schedule, which depends on exogenous pollution taxes, with a new schedule $S(\cdot)$, which reflects endogenous choice of taxes. To do so, we obtain an expression for τ/τ^* in terms of $\tilde{z}$, which we then substitute into (5).

To begin, our optimal tax rate calculations imply that

(8)
$$\frac{\tau^*}{\tau} = \frac{I^*}{I}\left(\frac{D^*}{D}\right)^{\gamma-1},$$

which means that we now must solve for both income and pollution in terms of $\tilde{z}$. Let $\varphi(\tilde{z}) \equiv \int_0^{\tilde{z}} b(z)\, dz$ denote the share of world spending on Northern goods. Then balanced trade requires that

$$I = \varphi(\tilde{z})(I + I^*). \tag{9}$$

Aggregate Northern pollution, D, is the sum of pollution generated by the production of Northern output:

$$D = \int_0^{\tilde{z}} d(z)\, dz = \int_0^{\tilde{z}} \frac{[\alpha(z)p(z)y(z)]}{\tau}\, dz = \int_0^{\tilde{z}} \left[\frac{\alpha(z)b(z)(I + I^*)}{\tau}\right] dz. \tag{10}$$

The second equality follows from our Cobb-Douglas production functions (recall that $\alpha(z)$ is the share of pollution charges in the cost of good z) and from the zero profit conditions. The third equality follows from the definition of $b(z)$. Combining (9) and (10), we obtain

$$D = I\theta(\tilde{z})/\tau\varphi(\tilde{z}), \tag{11}$$

where $\theta(\tilde{z}) \equiv \int_0^{\tilde{z}} \alpha(z)b(z)dz$ is the share of Northern pollution charges in world income.[13] Now use the optimal pollution tax formula (7) to eliminate τ from (11), and do the same for the South to obtain expressions for pollution:

$$D = \left(\frac{\theta(\tilde{z})}{\beta\varphi(\tilde{z})}\right)^{1/\gamma} \quad \text{and} \quad D^* = \left(\frac{\theta^*(\tilde{z})}{\beta\varphi^*(\tilde{z})}\right)^{1/\gamma}, \tag{12}$$

where $\varphi^*(\tilde{z}) = 1 - \varphi(\tilde{z})$ is the share of world spending on Southern goods, and

$$\theta^*(\tilde{z}) = \int_{\tilde{z}}^1 \alpha(z)b(z)\, dz$$

is the share of Southern pollution charges in world income.

We can now return to (8) and use the balance of trade condition (9) and our expressions for pollution in (12) to obtain relative pollution taxes as a function of $\tilde{z}$:

$$\frac{\tau^*}{\tau} = \left(\frac{\theta^*(\tilde{z})}{\theta(\tilde{z})}\right)^{(\gamma-1)/\gamma}\left(\frac{\varphi^*(\tilde{z})}{\varphi(\tilde{z})}\right)^{1/\gamma} \equiv \zeta(\tilde{z}). \tag{13}$$

Finally, substituting (13) into (5) yields the result that North will

13. To see this, note that the share of Northern pollution charges in world income is $\tau D/(I + I^*)$, and use (10).

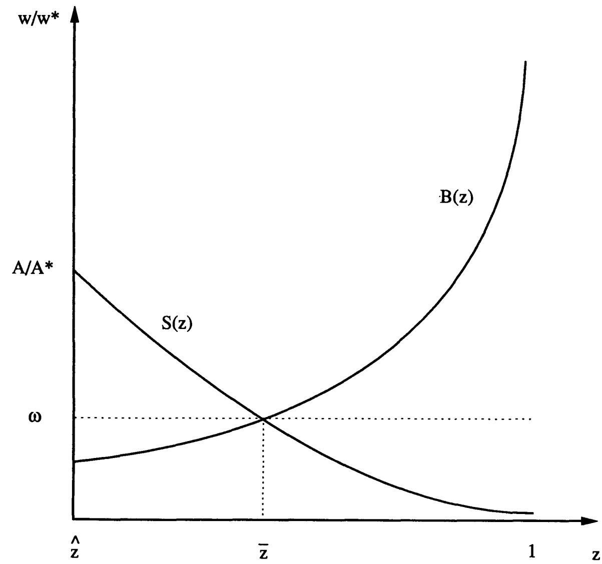

FIGURE II
Trading Equilibrium

produce all goods in the interval $[0,\tilde{z})$ if

$$\omega = \frac{A}{A^*}\,[\zeta(\tilde{z})]^{\alpha(\tilde{z})/(1-\alpha(\tilde{z}))} \equiv S(\tilde{z}), \tag{14}$$

provided that in equilibrium, $\tau > \tau^*$. The condition $\tau > \tau^*$ requires that $\zeta(\tilde{z}) < 1$. Thus, (14) is valid only for $\tilde{z} > \hat{z}$, where $\zeta(\hat{z}) \equiv 1$.[14] In this region S is decreasing in $\tilde{z}$;[15] we also have $S(\hat{z}) = A/A^*$, and $S(1) = 0$. The S schedule is plotted in Figure II.

To determine the equilibrium critical industry $\bar{z}$, we must combine $S(\tilde{z})$ with a balance of trade schedule that takes into account the resource constraints of the economy. Northern income is the sum of wages and pollution taxes (which are rebated to consumers). Hence

$$I = wL + \tau D. \tag{15}$$

14. Equation (14) is not valid outside this interval because the balance of trade condition (9) is constructed for the case where $\tau > \tau^*$. If $\bar{z} < \hat{z}$, we would have $\tau < \tau^*$, which is inconsistent with the pattern of trade implicit in (9). The case where $\tau \le \tau^*$ is discussed briefly below.

15.

$$\frac{d\ln(S(\tilde{z}))}{d\tilde{z}} = \left[\frac{\alpha'}{(1-\alpha)^2}\right]\ln(\zeta) - \left[\frac{\alpha}{(1-\alpha)^2}\right]\left\{\frac{(\gamma-1)\theta'\theta(1)}{\gamma\theta^*\theta + \varphi'/\varphi\varphi^*}\right\} < 0, \text{ since } \zeta < 1.$$

Using (11) to eliminate D in (15), and rearranging yields

$$I = \frac{wL\varphi(\tilde{z})}{\int_0^{\tilde{z}} b(z)[1 - \alpha(z)]dz}. \tag{16}$$

Following similar steps to obtain an expression for Southern income, and substituting into (9), we can solve for the balance of trade schedule:

$$\omega = \frac{\int_0^{\tilde{z}} b(z)[1 - \alpha(z)]\,dz}{\int_{\tilde{z}}^1 b(z)[1 - \alpha(z)]\,dz} \equiv B(\tilde{z}). \tag{17}$$

Note that $B(0) = 0$, $B(1) = \infty$, and $dB/d\tilde{z} > 0$. The $B(\tilde{z})$ schedule is positively sloped because an increase in the range of goods produced in the North raises exports and lowers imports, and must be met with an increase in North's relative wages to maintain balanced trade.

If $B(\tilde{z})$ and $S(\tilde{z})$ intersect at some $\tilde{z} = \bar{z} > \hat{z}$, as shown in Figure II, they determine an equilibrium where North produces all of the relatively clean goods (i.e., all $z < \bar{z}$), and South produces all of the relatively pollution-intensive goods (all $z > \bar{z}$).[16] We now show that this pattern of trade must obtain if a Northern worker's human capital endowment is sufficiently large relative to that of a Southern worker.

PROPOSITION 1. There exists an equilibrium with $\tau > \tau^*$, where North produces all goods $z \in [0,\bar{z})$ and South produces all goods, $z \in (\bar{z},1]$ if and only if $A/A^* > \delta > 1$, where $\delta \equiv B(\hat{z})$.

Proof of Proposition 1. See Appendix.

The intuition for this result is straightforward. If North has a relatively high income, it chooses a higher pollution tax. Consequently, this forces all of the pollution-intensive industries to locate in the South. Conversely, all of the relatively clean industries locate in the North. However, as the statement of the proposition makes clear, this result is reliant on relative factor endowments being sufficiently different. If this is not the case, then B and S will not intersect over the range $z \in [\hat{z},1]$, and other outcomes are possible.

16. The case where the two curves do not intersect to the right of $\hat{z}$ is discussed below.

First, the roles of South and North may be reversed: if South is sufficiently well endowed with human capital relative to North (i.e., if $A/A^* < 1/\delta$), then $\tau^* > \tau$, and there will be an equilibrium where the pattern of trade is reversed and North produces all of the pollution-intensive goods. Second, if Southern and Northern human capital levels are similar (i.e., if $1/\delta \leq A/A^* \leq \delta$), then a factor-price equalization equilibrium will arise. The two countries will choose identical pollution taxes, and the returns to *effective* labor units will be equalized. The pattern of trade in goods will be indeterminate, but as long as $A/A^* > 1$, the North will be a net exporter of embodied labor services, while the South will be a net exporter of embodied pollution services. Since our primary interest in this paper is in the effect of significant income differences on linkages between trade and the environment, we limit our discussion to equilibria where North chooses a higher pollution tax than the South.

IV. Trade and Pollution

One of the central questions raised by many of those concerned about linkages between trade and the environment is whether trade is inherently pollution-creating. Since trade in our model is driven entirely by income-induced international differences in pollution policy, it provides a useful framework in which to examine this question. By comparing free trade pollution levels with those in autarky, we obtain

PROPOSITION 2. If the assumptions of Proposition 1 hold, trade always lowers the pollution level in the North, increases the pollution level in the South, and increases worldwide pollution.

Proof of Proposition 2. See Appendix.

To investigate the intuition behind Proposition 2, it is useful to decompose the change in pollution levels into the scale, technique, and composition effects. Totally differentiating (11) (evaluated at the equilibrium) yields

$$dD = \frac{\partial D}{\partial I}\,dI + \frac{\partial D}{\partial \tau}\,d\tau + \frac{\partial D}{\partial \bar{z}}\,d\bar{z}. \tag{18}$$

Similar decompositions can be carried out for Southern and World pollution.

The *scale effect* reflects the increase in pollution created by an increase in the level of economic activity in the relevant jurisdiction, holding constant the techniques of production and the composition of final output. For the North it is represented by the first term in (18). This effect must be positive, and in fact, pollution must rise in direct proportion to income if tastes are homothetic (implying an equal percentage increase in the demand for all goods), and if technologies exhibit constant returns to scale (ensuring that these increases in output are met by an equal percentage increase in labor input and pollution discharge). This is confirmed by differentiating (11):

$$(19) \qquad \frac{\partial D}{\partial I} = \frac{\theta(\bar{z})}{\tau\varphi(\bar{z})} > 0, \qquad \text{and} \qquad \frac{\partial D}{\partial I}\frac{I}{D} = 1.$$

Similarly, the scale effect in the South is positive and proportional to income.

The *technique effect* measures the change in aggregate pollution arising from a switch to less pollution-intensive production techniques, holding constant income and the range of goods produced. Since an increase in pollution taxes leads to the adoption of cleaner production methods, the technique effect, given by the second term in (18), must be negative:

$$(20) \qquad \frac{\partial D}{\partial \tau} = -\frac{I\theta(\bar{z})}{\tau^2\varphi(\bar{z})} < 0.$$

Similarly, $\partial D^*/\partial\tau^* < 0$. Moreover,

$$\frac{\partial D}{\partial \tau}\frac{\tau}{D} = \frac{\partial D^*}{\partial \tau^*}\frac{\tau^*}{D^*} = -1.$$

This follows directly from our assumptions on the substitution possibilities in production and consumption which imply that τD is constant when both I and $\bar{z}$ are held constant:

$$\tau D = \int_0^{\bar{z}} \tau d(z)\,dz = \int_0^{\bar{z}} \alpha(z)p(z)y(z)\,dz$$
$$= \int_0^{\bar{z}} \alpha(z)b(z)[I + I^*]\,dz = \int_0^{\bar{z}} \frac{\alpha(z)b(z)I}{\varphi(\bar{z})}\,dz.$$

The second equality holds because the elasticity of substitution in production is one, and the third holds because the elasticity of substitution in consumption is one. (The final equality follows from the balance of trade condition.) The preceding suggests that if the elasticities of substitution in production or consumption exceed one, we expect a larger technique effect, and if they are less than one, we expect a smaller technique effect.

Finally, the *composition* effect measures the change in pollution due to a change in the range of goods produced by a country. For the North this effect is captured by the third term in (18). Differentiation of (11) yields

$$\text{(21)} \qquad \frac{\partial D}{\partial \bar{z}} = D\left[\frac{\theta'(\bar{z})}{\theta(\bar{z})} - \frac{\varphi'(\bar{z})}{\varphi(\bar{z})}\right] = \frac{Ib(\bar{z})}{\tau\varphi(\bar{z})^2}\int_0^{\bar{z}} [\alpha(\bar{z}) - \alpha(z)]b(z)\,dz > 0,$$

since α is increasing in z. Thus, pollution rises in response to an increase in the range of goods produced in the North, if income and pollution taxes are held constant. This is because marginal goods added to Northern production are more pollution intensive than the original goods. Allocating a given Northern labor force across a group of industries that has become, on average, more pollution intensive must raise Northern pollution.

In the South we obtain

$$\frac{\partial D^*}{\partial \bar{z}} = \frac{I^*b(\bar{z})}{\tau^*\varphi^*(\bar{z})^2}\int_{\bar{z}}^{1} [\alpha(z) - \alpha(\bar{z})]b(z)\,dz > 0.$$

The composition effect for the South due to an increase in $\bar{z}$ is also positive. However, note that in this case, an increase in $\bar{z}$ corresponds to a *decrease* in the range of products produced by the South. As $\bar{z}$ increases, South loses its cleanest industries, leading to an increase in average pollution intensity. With a given production capacity, overall pollution must rise. Conversely, the composition effect due to an *increase* in the range of industries produced by the South (*a* fall in $\bar{z}$) leads to a *decrease* in Southern pollution. Thus, the composition effect works to increase pollution in a country if it leads to an increase in the average pollution intensity of production (i.e., if dirty industries are attracted to a region or if clean industries leave), and it leads to a decrease in pollution if the average pollution intensity falls.

With these definitions in hand, we can now show that although international trade changes the range of goods produced in each country (a composition effect), increases real incomes (a scale effect), and creates incentives for governments to adjust their pollution taxes (a technique effect), the composition effect always dominates the other two effects. To examine the net result of these three effects, use (19)–(21) to rewrite (18) in percent change notation. Letting $\hat{D} = dD/D$, etc., this yields

$$\hat{D} = \hat{I} - \hat{\tau} + (\hat{\theta} - \hat{\varphi}), \tag{22}$$

where $\hat{I}$ is the scale effect, $-\hat{\tau}$ is the technique effect, and $\hat{\theta} - \hat{\varphi}$ is the composition effect.[17] The change in the pollution tax can be obtained from (7):

$$\hat{\tau} = (\gamma - 1)\hat{D} + \hat{I}. \tag{23}$$

Combining the above two expressions and rearranging yields

$$\hat{D} = -\ [(\gamma - 1)/\gamma](\hat{\theta} - \hat{\varphi}) + (\hat{\theta} - \hat{\varphi}). \tag{24}$$

The first term is the net result of the scale and technique effects. If $\gamma = 1$, this term disappears: the technique effect exactly offsets the scale effect. When $\gamma > 1$, pollution taxes respond more than proportionately to a change in income if pollution rises. As a result, the technique effect not only fully offsets the scale effect, but also offsets a fraction $(\gamma - 1)/\gamma$ of the composition effect. However, the composition effect must always dominate: from (24) we have

$$\hat{D} = (\hat{\theta} - \hat{\varphi})/\gamma. \tag{25}$$

Thus, while a larger γ dampens the magnitude of response of pollution to changes in the economy, the direction of the change is always determined by the sign of the composition effect $(\hat{\theta} - \hat{\varphi})$.

To understand why the composition effect dominates, it is useful to reinterpret trade in goods as implicit trade in factor services. The model behaves much like a two-factor Heckscher-Ohlin model with one factor in variable supply (pollution in our case) and one factor in inelastic supply (effective labor).[18] Hence by constructing pollution demand and supply, we can show that trade is driven by differences in relative factor supplies, and that when the South has an opportunity to trade, it can increase its gains from trade by accepting an increase in pollution.

Combining the optimal tax condition (7) and the economy's budget constraint (15) yields an expression for the inverse supply of pollution in the North:

$$\frac{\tau}{w_e} = \frac{\beta A(h) L D^{\gamma-1}}{1 - \beta D^{\gamma}}, \tag{26}$$

where $w_e = w/A(h)$ is the return to a unit of effective labor. This is

17. Note that $\hat{\theta} = \theta' d\,\bar{z}/\theta$ and $\hat{\varphi} = \varphi' d\,\bar{z}/\varphi$. Also, note from (21) that $\hat{\theta} - \hat{\varphi} > 0$ for $d\,\bar{z} > 0$.

18. We are grateful to Alan Deardorff for suggesting this interpretation.

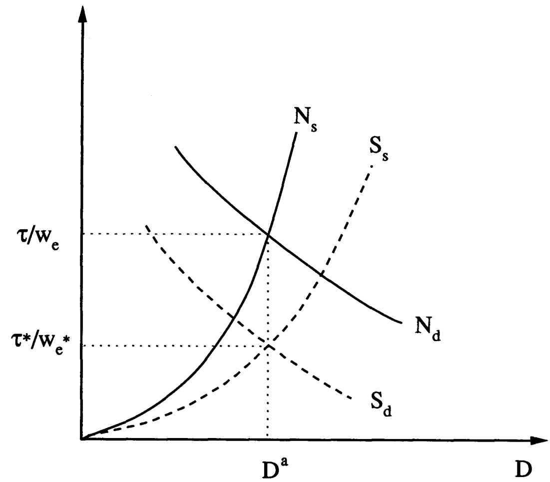

FIGURE III
Pollution Supply and Demand

plotted in Figure III and labeled N_s. The supply of pollution is increasing in τ/w_e since consumers are willing to accept increases in pollution if they are compensated with higher revenue from pollution taxes.

The derived demand for pollution in autarky (i.e., the pollution implicit in the demand for consumer goods) can be obtained by setting $\bar{z} = 1$ in (11), and combining with the economy's budget constraint to obtain

$$\frac{\tau}{w_e} = \frac{A(h)L\theta(1)}{D[1 - \theta(1)]}. \tag{27}$$

This is plotted as N_d in Figure III. As one would expect, the derived demand for pollution is decreasing in its relative price, τ/w_e.

Equating the demand and supply for pollution in the North yields the autarky factor price ratio (τ/w_e), and autarky pollution level,

$$D^a = \left(\frac{\theta(1)}{\beta}\right)^{1/\gamma}. \tag{28}$$

Note that a reduction in human capital shifts down both the demand and supply curves by the same proportion (as indicated by the two dashed lines S_s and S_d in Figure III). This leaves the pollution level unchanged, but reduces τ/w_e.[19] Since the South differs from the North only in that it has less human capital, we conclude that pollution is a relatively scarce input in the North prior to trade ($D^a/AL < D^a/A^*L$), and consequently, that pollution is relatively more costly for firms in the North than in the South ($\tau/w_e > \tau^*/w_e^*$).

This provides a basis for trade. North is willing to export effective labor services (embodied in goods) in return for imports of pollution services, and South is willing to do the reverse. Since trade increases the demand for pollution services in the South, and reduces the demand in the North, it reduces the gap between factor prices by raising τ^*/w_e^* and reducing τ/w_e. Since the supply curves are valid both in trade and autarky, we see from Figure III that trade must therefore increase pollution in the South (a movement up its pollution supply curve) and reduce pollution in the North (a movement down its supply curve). Increases in γ make the supply curves more inelastic, but the direction of the response is not altered, since trade is driven by pressures to reduce the gap in factor prices across countries.

The last result in Proposition 2 is that total world pollution rises with trade. The change in world pollution is the net result of the scale, technique, and composition effects in both countries. We have already shown that the composition effect dominates the scale and technique effects; and therefore to understand how world pollution responds to trade, we need to consider the strength of the two opposing composition effects.

Trade shifts some of the Northern labor force from dirty industries into clean ones, and shifts some of the Southern labor force from clean industries into dirty ones. To examine the consequences of these reallocations, consider the movement of one unit of Southern effective labor from a clean industry in the South (z') to a dirty industry in the South (z''). At the same time, shift one unit of Northern effective labor from a dirty industry in the North (z'') to a clean industry in the North (z'). The change in pollution in each country can be deduced from the local $d(z)/l(z)$ ratio. Using (2), we can infer that the induced change in pollution in the North is

$$\Delta d_N = \frac{d(z')}{l(z')} - \frac{d(z'')}{l(z'')} = \frac{w_e}{\tau}\left[\frac{\alpha(z')}{1-\alpha(z')} - \frac{\alpha(z'')}{1-\alpha(z'')}\right] < 0,$$

19. Pollution is not, however, independent of country size, since β depends on L. The effect of country size is discussed in Section VII.

since $\alpha(z') < \alpha(z'')$. A similar calculation for the South yields $\Delta d_S > 0$. Adding, to determine the net effect of this reallocation on world pollution, we obtain

$$\Delta d_N + \Delta d_S = \left[\frac{\alpha(z'')}{1-\alpha(z'')} - \frac{\alpha(z')}{1-\alpha(z')}\right]\left[\frac{w_e^*}{\tau^*} - \frac{w_e}{\tau}\right].$$

Since trade reduces but does not eliminate the gap between relative factor prices, we have $w_e^*/\tau^* > w_e/\tau$, and therefore $\Delta d_N + \Delta d_S > 0$. This combined world composition effect raises world pollution provided that factor prices are not equalized across countries.[20]

V. Trade, Pollution, and Economic Development

The previous section showed that opening a country up to trade affects both the level and distribution of world pollution. These results were driven mainly by changes in the location of production since the output-enhancing effects of trade were offset by changes in pollution policy. In the present section we focus on the effects of changes in production capacity on pollution, by examining the consequences of increases in human capital.

Let us first consider the effects of growth on pollution in autarky. An increase in the level of human capital stimulates pollution directly through the scale effect. In Figure III this corresponds to an outward shift in the demand for pollution. Because of higher income, the pollution supply curve shifts inward. This increases the τ/w_e ratio, but since the demand and supply for pollution are proportional to the economy's endowment of effective labor, the scale and technique effects exactly offset each other, leaving the level of pollution unaffected by economic growth. Note that there is no composition effect in autarky since tastes are homothetic.[21] The result that growth has no effect on pollution in autarky is specific to our assumptions on substitution possibilities, but it nevertheless provides a very useful benchmark. Any change in pollution induced by trade or growth in the open economy version of our model must be driven entirely by the opportunity to

20. As may be expected from our simple argument above, it is straightforward to show that if North and South are sufficiently similar so that pollution taxes are equalized by trade, then free trade has no effect on global pollution levels. However, trade will still alter the distribution of pollution across countries with the human-capital-rich country reducing its pollution level while the human-capital-poor country increases its pollution level.

21. If demand shifted to relatively clean goods (such as services) as income rose, then there would be a composition effect in autarky. We leave the investigation of nonhomothetic preferences for future work.

trade, and not by the simple effects of increases in the level of economic activity.

We next consider symmetric growth in the world economy. Suppose that there is equiproportionate, labor-augmenting technological progress. With $dA/A = dA^*/A^* > 0$, neither the $S(z)$ nor the $B(z)$ schedule is affected, and hence (referring to Figure II) ω and $\bar{z}$ are unchanged. Since $\bar{z}$ does not change, then from (12), pollution levels are unchanged. As in autarky, symmetric growth across countries increases the world's productive capacity and raises pollution through the scale effect, but this is just offset by the technique effect as pollution taxes respond to higher income levels. With equiproportionate growth in both countries the terms of trade remain constant—there is no reallocation of industries across countries, and hence no composition effect. World pollution remains constant.

Now consider asymmetric growth. Suppose that there is an increase in the level of human capital in the North, holding the level of Southern human capital constant. This shifts the $S(z)$ schedule upwards, while leaving $B(z)$ unaffected. From Figure II it is apparent that North's relative wage rises ($d\omega/dh > 0$), and the range of commodities produced in the North grows ($d\bar{z}/dh > 0$). The effect on Northern pollution is obtained by differentiating (12):

$$\frac{dD}{dh} = \frac{1}{\gamma}\left[\frac{b(\bar{z})D}{\theta(\bar{z})\varphi(\bar{z})}\int_0^{\bar{z}} b(z)[\alpha(\bar{z}) - \alpha(z)]\,dz\right]\frac{d\bar{z}}{dh} > 0, \tag{29}$$

since α is increasing in z. Northern pollution increases, even though the government has an opportunity to adjust the pollution tax rate.

To understand this result, recall that North's government adjusts the pollution tax so that the technique effect fully offsets the scale effect, and partially offsets the composition effect. That is, if $\bar{z}$ were held constant, pollution levels in the North would be unaffected by the increase in output generated by the increase in human capital. However, $\bar{z}$ cannot remain constant since the North's production of exportables and its demand for importables both rise. A fall in North's terms of trade is required to maintain balanced trade. This induces Southern industries to migrate to the North. Thus, the effect of growth on pollution is determined by the composition effect. This can be confirmed by referring to (21), and noting that the term in brackets in (29) is simply $\partial D/\partial \bar{z}$. Because the marginal Southern industries that move northward are more pollution intensive than existing Northern industries, the composition effect is positive, and Northern pollution rises.

To determine the effect of Northern growth on Southern pollution, differentiate (12):

$$\frac{dD^*}{dh} = \frac{1}{\gamma}\left[\frac{b(\bar{z})D^*}{\theta^*(\bar{z})\varphi^*(\bar{z})}\int_{\bar{z}}^{1} b(z)[\alpha(z) - \alpha(\bar{z})]\, dz\right]\frac{d\bar{z}}{dh} > 0.$$

Once again, the composition effect determines the direction of the change in pollution. An increase in $\bar{z}$ shifts South's least pollution-intensive industries to the North. As a result, the average pollution intensity in the South rises, and with a given labor force, this increases total pollution.

In contrast, economic development in the South lowers pollution in both countries. An increase in Southern human capital shifts down the $S(z)$ schedule in Figure II, and both ω and $\bar{z}$ fall. South's economy expands, but the marginal industries it attracts from the North are less pollution intensive than existing Southern industries. Hence the composition effect is negative, and Southern pollution falls. The composition effect in the North is also negative since the North loses its most pollution-intensive industries to the South; hence Northern pollution also falls.

To summarize, we have found that as rich countries get richer, world pollution increases, but as poor countries get richer, world pollution falls. The intuition for these surprising results can best be understood with the aid of Figure III. Growth increases a country's supply of effective labor, which raises its autarky τ/w_e ratio. When growth occurs in the North, the differences between the two countries are magnified. This widens the gap between both pre- and posttrade factor prices. But recall that it is the gap between posttrade factor prices that determines the strength of the overall world composition effect. A greater gap between factor prices means a greater difference in techniques across countries, and a greater increase in pollution arising from concentrating dirty industries in the lower income country. When growth occurs in the South, the opposite occurs. Factor supply ratios move closer together, shrinking the gap between factor prices. The world composition effect is muted, and hence pollution falls. Therefore, our results here provide a corollary to Proposition 2.

COROLLARY. The increase in pollution accompanying trade is greater, the greater are the differences across countries in human capital endowments.

VI. Transfers, Trade, and Pollution

In this section we consider the impact of an income transfer from North to South. In the basic Dornbusch-Fischer-Samuelson [1977] model, transfers have no real effects because there are identical homothetic preferences and no public goods. In the present model, transfers have real effects since they alter relative income levels, and hence relative pollution taxes. The transfer case is important to consider because unlike the asymmetric growth experiments conducted above, a transfer provides us with an example of a change in the world distribution of income that is not accompanied by changes in production capacity. Consequently, it allows us to focus on pure income effects. The study of transfers is also of interest because a theme in the recent literature on trade and the environment is that tied aid can be used to reduce pollution in the South. In this section we show that untied aid can accomplish the same objective.

To proceed, we derive a modified $S(\cdot)$ schedule that incorporates transfers. Once this schedule is constructed, we can again use Figure II to generate comparative static results. Let T be the value of the transfer (measured in terms of Northern labor), and let I and I^* be the level of income (excluding transfers) generated within each country. Then it is straightforward to show that pollution taxes are given by

$$(30) \qquad \tau = \beta D^{\gamma-1}(I - T) \qquad \text{and} \qquad \tau^* = \beta D^{*\gamma-1}(I^* + T).$$

Using a derivation analogous to that which led to (12), we obtain pollution levels:

$$(31) \quad D = \left(\frac{I\theta(\tilde{z})}{(I-T)\beta\varphi(\tilde{z})}\right)^{1/\gamma} \qquad \text{and} \qquad D^* = \left(\frac{I^*\theta^*(\tilde{z})}{(I^*+T)\beta\varphi^*(\tilde{z})}\right)^{1/\gamma}.$$

Combining (30) and (31) and letting

$$(32) \qquad h(T,\tilde{z}) = \frac{T}{\varphi(\tilde{z})(I-T)} > 0,$$

we can obtain an expression for the ratio of pollution taxes:

$$(33) \qquad \frac{\tau^*}{\tau} = \left(\frac{\theta^*(\tilde{z})}{\theta(\tilde{z})}\right)^{(\gamma-1)/\gamma}\left(\frac{\varphi^*(\tilde{z})}{\varphi(\tilde{z})} + h(T,\tilde{z})\right)^{1/\gamma} \equiv \zeta(\tilde{z},T).$$

Note that (33) differs from (13) only by the presence of the term $h(T,\tilde{z})$. It is easy to show that $\partial h/\partial T > 0$, $\partial h/\partial \tilde{z} < 0$, and $h(0,\tilde{z}) = 0$; and hence (33) reduces to (13) when there is no transfer. Also note that with Northern labor as the numeraire, h is a function of $\tilde{z}$ and T, but not of ω.

A modified $S(\cdot)$ schedule is obtained by substituting (33) into (4):

$$\omega = \frac{A}{A^*}[\zeta(\tilde{z},T)]^{\alpha(\tilde{z})/(1-\alpha(\tilde{z}))} \equiv S(\tilde{z},T). \tag{34}$$

Since h is decreasing in $\tilde{z}$, $S(\tilde{z},T)$ is also decreasing in z, provided that North remains the high income country after the transfer; i.e., provided that $I - T > I^* + T$. Also, since $h(0,\tilde{z}) = 0$, the modified $S(\tilde{z},T)$ schedule coincides with the original $S(\tilde{z})$ schedule for $T = 0$.

A transfer has no effect on $B(\tilde{z})$, but $S(\tilde{z},T)$ shifts up as T rises. Hence by interpreting the S schedule as a function of $\tilde{z}$ and T, we can use Figure II to conclude that a transfer raises both $\bar{z}$ and ω. The reasoning is straightforward. A transfer from North to South reduces North's relative income, and hence its relative pollution tax falls, rendering Northern industries more competitive. As a result, North attracts marginal industries from the South ($\bar{z}$ rises). This increases the relative demand for North's labor, pushing up its relative wage, but not by enough to offset the direct effect of the transfer.

Let us now consider the effects of the transfer on pollution. Define $\sigma(T) = (I - T)/(I + I^*)$ to be the share of income accruing to the North after the transfer is applied. We confine ourselves to the case where $\sigma(T) > 1$; that is, where North continues to be the relatively rich country. Note that a transfer must lower North's consumption share of world income; that is, $d\sigma/dT < 0$.[22] Using (31), Northern pollution can be written as

$$D(T) = \left(\frac{\theta(\bar{z})}{\beta\sigma(T)}\right)^{1/\gamma}.$$

Differentiating with respect to T shows that the transfer leads to an increase in North's pollution:

$$\frac{dD}{dT} = \frac{D}{\gamma}\left[-\frac{\sigma'}{\sigma} + \frac{\alpha(\bar{z})b(\bar{z})}{\theta}\frac{d\bar{z}}{dT}\right] > 0, \tag{35}$$

where $\sigma' \equiv d\sigma/dT$. North reduces its pollution tax in response to its

22. Since $\tau^*/\tau = (1 - \sigma)/\sigma$, we have $\sigma(T) = 1/(1 + \tau^*/\tau)$. Moreover, note that since $d\bar{z}/dT > 0$, we must have $d(\tau^*/\tau)/dT > 0$; and hence $\sigma'(T) < 0$. Note that this is not a partial derivative, as it includes both the direct and indirect effects of the transfer on σ.

lower disposable income, and this tends to increase pollution via the technique effect.[23] As well, the decline in North's pollution tax attracts marginal industries from the South, and since these new industries are relatively pollution intensive, the composition effect also tends to increase North's pollution.

Conversely, South's pollution falls in response to the transfer:

$$\frac{dD^*}{dT} = \frac{D^*}{\gamma}\left[\frac{\sigma'}{1-\sigma} - \frac{\alpha(\bar{z})b(\bar{z})}{\theta^*}\frac{d\bar{z}}{dT}\right] < 0. \tag{36}$$

In the South, disposable income increases, its pollution tax rises, and pollution falls from the technique effect. However, its marginal industries migrate to the North, and since these are relatively clean, the average pollution intensity of South's industries rises for given techniques. Consequently, Southern pollution should rise from the composition effect. However, as (36) shows, the direct effect of the pollution tax increase more than offsets this indirect composition effect: pollution falls in the South. Direct effects swamp indirect effects since the increase in the pollution tax affects the pollution intensity of all Southern industries, and all of these industries are more pollution intensive than the marginal ones given up.

Finally, we show that a small transfer must lower world pollution. Summing (35) and (36) and evaluating at $T = 0$ noting that at this point $\sigma(T) = \varphi(\bar{z})$ yields

$$\left.\frac{d(D+D^*)}{dT}\right|_{T=0} = \left(\frac{\sigma'}{\gamma}\right)\left[\frac{D^*}{1-\varphi(\bar{z})} - \frac{D}{\varphi(\bar{z})}\right] + \frac{\alpha(\bar{z})b(\bar{z})(I+I^*)}{\gamma}\left[\frac{1}{\tau} - \frac{1}{\tau^*}\right]\frac{d\bar{z}}{dT} < 0.$$

Putting the technique and composition effects from both countries together, world pollution must fall. This follows since the transfer raises pollution taxes in the most pollution-intensive country, and reduces the disparity in techniques used worldwide.[24]

23. Note that the technique effect is usually offsetting a scale effect, but that in this case there is no direct scale effect, since North's underlying production capacity is not affected by the transfer.

24. The effects of a transfer on pollution can be summarized by appealing to Figure III one last time. A transfer shifts out the donor's supply of pollution (since environmental quality is a normal good), and shifts in the recipient's supply function. This reduces the gap between autarky factor price ratios, reduces the incentives to trade to exploit differences in pollution policy, and thereby reduces world pollution. South to North transfers have opposite effects.

VII. Extensions

This section extends the model to examine the implications of cross-country differences in population density, climate, and other factors that affect the damage caused by pollution. These modifications would be an important preliminary step to empirically testing the model.

Consider the following specification for the utility function:

$$U = \int_0^1 b(z) \ln [x(z)]\, dz - \beta_0 \left[\frac{D}{L} g(\rho)\right]^\gamma \Big/ \gamma \tag{37}$$

where $\beta_0 > 0$ is a constant, and $g'(\rho) > 0$. This corresponds to setting

$$\beta(L,\rho) = \beta_0[g(\rho)/L]^\gamma \tag{38}$$

in (3). In this specification, increases in either pollution per capita or in population density (for given pollution levels) reduce utility by increasing the exposure of a typical person to pollution.

Let us now reconsider autarky pollution. Substituting (38) into (28) yields

$$\frac{D^a}{L} = \frac{(\theta(1)/\beta_0)^{1/\gamma}}{g(\rho)}. \tag{39}$$

If two countries have the same population density, then pollution per capita is the same across countries. This means that if we scale up the size of a country, by increasing both land mass and population proportionately, then aggregate pollution rises. This is a reasonable prediction for pollution that has localized effects. On the other hand, as population density increases, pollution per capita falls, since a given unit of pollution causes more damage in a more crowded environment.

Let us now consider trade. First, suppose that two countries differ only with respect to labor force size, but are otherwise identical in terms of population density and human capital. In this case, there is no basis for trade. The larger country is just a scaled-up version of the smaller, and relative factor supplies are identical. Not surprisingly, in a constant returns to scale world with equal relative factor supplies, autarky prices are identical, and free trade is identical to autarky. This is confirmed by substituting

(39) into (27) to obtain the autarky factor price ratio:

$$\frac{\tau}{w_e} = \frac{A(h)[\theta(1)^{\gamma-1}\beta_0]^{1/\gamma}g(\rho)}{1 - \theta(1)},$$

which is independent of L.

Next suppose that North and South are identical in all respects, except that North is more densely populated. Then from (26), (27), and (38), North's pollution supply curve will be to the left of South's, and hence the autarky τ/w_e ratio will be relatively higher in the North. Thus, in free trade the more densely populated country will export labor-intensive goods, while the less densely populated country will export pollution-intensive goods.

If countries differ both with respect to the level of human capital and population density, then the pattern of trade depends on the interaction between the two effects. If the human-capital-poor country is less densely populated than the rich country, then its tendency to specialize in pollution-intensive goods will be reinforced. However, if the poor country is more densely populated than the rich country, then its supply curve for pollution will shift inward, and the pattern of trade may be reversed, with the poor country exporting relatively clean goods.

Finally, suppose that two countries differ with respect to the carrying capacity of the environment, as determined by prevailing winds, ocean currents, soil conditions, and other factors. This may be captured by allowing the β function to differ across countries. Suppose that a given unit of pollution causes less damage at Home than abroad because of differences in the environment. Then for any given L and ρ, we have $\beta(L,\rho) < \beta^*(L,\rho)$. Consequently, if the countries are otherwise identical, Home's supply of pollution will be to the right of Foreign's, and hence Home exports pollution-intensive goods.

VIII. Conclusion

This paper has presented a simple model to examine how trade between two countries differentiated solely by income can affect environmental quality. Our most important results are that income gains arising from an opportunity to trade can affect pollution in a different way than income gains obtained through economic growth and, moreover, that economic growth has different effects on pollution in a free trade regime than in autarky.

If environmental policy is set optimally, then potential increases in pollution generated by economic growth in autarky can be prevented by a policy-induced switch to cleaner methods of production. Given our assumption on substitution possibilities in production and consumption, growth in autarky has a neutral effect on pollution: the technique effect fully offsets the scale effect.

However, international trade opens up a different channel that may nevertheless lead to an increase in world pollution. While trade, like growth, increases real incomes in both countries, it also creates a composition effect that is critical in determining the effect of trade on pollution. If differences in pollution taxes are the only motive for trade, and trade does not equalize factor prices, then a movement from autarky to free trade increases aggregate world pollution.

Composition effects also determine the impact of asymmetric economic growth on pollution in free trade. Even if, as in our model, the pollution-generating effects of symmetric growth across countries are exactly offset by stricter environmental policy, the migration of industries induced by asymmetric growth has important and interesting effects on pollution through the composition effect. Consequently, economic growth in the North has much different effects on the environment than economic growth in the South.

While our model is stylized and many of its particular results model-specific, much of the intuition springs from more general factor endowment considerations. Most of our results follow from just two suppositions: (1) trade has a tendency to reduce, but not fully eliminate, international differences in factor prices if countries are sufficiently different; and (2), in autarky, the relative price of pollution-intensive goods is higher in relatively high-income countries. The first of these suppositions is a quite general result. The second is much more tenuous, but it clearly holds in our simple model. In more general factor endowment models it may not. Nevertheless, the simple structure of our model is a virtue since it lays bare the basic relationships driving our results, and at once suggests extensions of the model that can only enhance our understanding of the relationship between pollution and international trade.

APPENDIX

A. Derivation of Equation (1) from a Joint Production Technology

The following is one way to motivate equation (1). Let l_y be the amount of effective labor used to produce good y. Since the analysis applies to any good, we suppress the index z to economize on notation. Assume that

$$y = \lambda^{\alpha} l_y, \tag{A1}$$

$$d_0(y) = \lambda^{(1-\alpha)} y = \lambda l_y, \tag{A2}$$

where d_0 is the amount of pollution produced in the absence of any abatement activity.

The firm has an abatement technology given by

$$A[l_a, d_0(y)] = d_0(y) - \left[\frac{\lambda^{\alpha-1} d_0(y)}{[d_0(y)/\lambda + l_a]^{1-\alpha}}\right]^{1/\alpha},$$

where l_a is the amount of effective labor assigned to abatement. Note that $A[0, d_0(y)] = 0$, and that $\partial A / \partial l_a > 0$, so that there is no abatement unless labor is allocated to it, and that an increase in labor assigned to abatement yields an increase in abatement. In addition, note that the abatement function is concave in l_a, and is asymptotic to $d_0(y)$, reflecting an assumption of diminishing returns to abatement activity.

Pollution discharged by the firm is equal to the unconstrained level of pollution, less the amount abated:

$$d(y, l_a) = d_0(y) - A[l_a, d_0(y)] = \left[\frac{\lambda^{\alpha-1} d_0(y)}{[d_0(y)/\lambda + l_a]^{1-\alpha}}\right]^{1/\alpha}. \tag{A3}$$

Using (A1) and (A2), we can rewrite (A3) as

$$d(y, l_a) = \left[\frac{y}{[l_y + l_a]^{1-\alpha}}\right]^{1/\alpha}. \tag{A4}$$

Letting $l = l_y + l_a$ be the total effective labor employed by the firm, we can rearrange (A4) to obtain

$$y = d^{\alpha} l^{1-\alpha}. \tag{A5}$$

Note that we require $l_a \geq 0$ and $l_y \geq 0$. Hence since $y = \lambda^{\alpha} l_y$, equation (A5) is valid only for $y \leq \lambda^{\alpha} l$, or equivalently, for $d \leq \lambda l$. Thus, output is not feasible for $d/l > \lambda$.

B. Conditions for an Interior Solution

To ensure an interior solution (i.e., that all firms engage in at least a small amount of abatement), we assume that $d/l < \lambda$ for all firms. Because Southern firms are the most pollution intensive, it is sufficient to ensure that this holds for the South. Using (2), we require that $\tau^*/w^* > \alpha(z)/[\lambda A^*(1 - \alpha(z))]$, for all z. Using the Southern version of (7) and (16) to eliminate τ^*/w^*, this is equivalent to requiring that

$$\text{(A6)} \qquad A^*L > \frac{\alpha(z)[\varphi^*(\bar{z}) - \theta^*(\bar{z})]}{\lambda\beta[1 - \alpha(z)]D^{*\gamma-1}\varphi^*(\bar{z})}, \qquad \text{for all } z.$$

But from Proposition 2, $D^* > D^a$, which implies that $\theta^*(\bar{z}) > \varphi^*(\bar{z})\theta(1)$. Hence we have

$$\text{(A7)} \qquad \frac{\varphi^*(\bar{z}) - \theta^*(\bar{z})}{D^{*\gamma-1}\varphi^*(\bar{z})} < \frac{1 - \theta(1)}{[\theta(1)/\beta]^{(\gamma-1)/\gamma}}.$$

Using (A7) in (A6), and noting that $\alpha(z) < \bar{\alpha}$, we conclude that the following condition is sufficient to ensure that $d/l < \lambda$ for all z (in either country):

$$AL > A^*L > \frac{\bar{\alpha}[1 - \theta(1)]}{\lambda\beta^{1/\gamma}(1 - \bar{\alpha})\theta(1)^{(\gamma-1)/\gamma}}.$$

The following make the condition more likely to be satisfied: (1) an increase in β, which corresponds to an increase in the disutility of pollution; (2) an increase in A^*L, which increases the willingness to pay to control pollution; (3) an increase in λ, which is the unregulated d/l ratio; and (4) an increase in $\theta(1)$, which is a weighted average of the pollution share parameters α.

C. Proofs of Propositions

The following inequalities are useful:

$$\text{(A8)} \qquad \theta(\bar{z}) < \alpha(\bar{z})\varphi(\bar{z}),$$

$$\text{(A9)} \qquad \theta^*(\bar{z}) > \alpha(\bar{z})\varphi^*(\bar{z}).$$

$$\text{(A10)} \qquad \varphi(\hat{z}) > 1/2.$$

The first two follow since α is increasing in z. The third follows from the definition of $\hat{z}$.

Proof of Proposition 1. (i) Sufficiency. B and S are both continuous. Also B is strictly increasing, and S is strictly decreasing for $z > \hat{z}$. Hence if $B(\hat{z}) < S(\hat{z}) = A/A^*$, they must intersect at some $z \in (\hat{z},1)$. (ii) Necessity. If $B(\hat{z}) > A/A^*$, then (17) and (14) cannot be solved for $\bar{z} > \hat{z}$. But for $\bar{z} \leq \hat{z}$, we have $I \leq I^*$, which is inconsistent with $\tau > \tau^*$ (and hence the construction of B and S is not valid). (iii) Finally, to show that $\delta > 1$, note that using (A8)–(A10), we have $\delta > \varphi(\hat{z})/\varphi^*(\hat{z}) > 1$.

QED

Proof of Proposition 2. Using a derivation similar to that which led to (12), we obtain an expression for autarky pollution levels:

$$D^a = D^{*a} = \left(\frac{\theta(1)}{\beta}\right)^{1/\gamma}.$$

Free trade pollution is given by (12). Subtracting yields

$$\text{(A11)} \qquad D - D^a = \beta^{-1/\gamma}\left[\left(\frac{\theta(\bar{z})}{\varphi(\bar{z})}\right)^{1/\gamma} - \theta(1)^{1/\gamma}\right].$$

Since $\theta(1) = \theta(\bar{z}) + \theta^*(\bar{z})$, and using (A8) and (A9), we have

$$\frac{\theta(\bar{z})}{\varphi(\bar{z})} - \theta(1) = \frac{\theta(\bar{z})\varphi^*(\bar{z}) - \varphi(\bar{z})\theta^*(\bar{z})}{\varphi(\bar{z})} < \frac{\alpha(\bar{z})\varphi(\bar{z})\varphi^*(\bar{z}) - \varphi(\bar{z})\alpha(\bar{z})\varphi^*(\bar{z})}{\varphi(\bar{z})} = 0.$$

Hence $\theta(\bar{z})/\varphi(\bar{z}) < \theta(1)$. But since the inequality is preserved by a monotonic transformation, we conclude that $[\theta(\bar{z})/\varphi(\bar{z})]^{1/\gamma} < [\theta(1)]^{1/\gamma}$, and hence $D < D^a$.

Turning now to the South, a similar analysis yields

$$\text{(A12)} \qquad D^* - D^{*a} = \beta^{-1/\gamma}\left[\left(\frac{\theta^*(\bar{z})}{\varphi^*(\bar{z})}\right)^{1/\gamma} - \theta(1)^{1/\gamma}\right].$$

Proceedings as above, we have

$$\frac{\theta^*(\bar{z})}{\varphi^*(\bar{z})} - \theta(1) = \frac{\theta^*(\bar{z})\varphi(\bar{z}) - \varphi^*(\bar{z})\theta(\bar{z})}{\varphi^*(\bar{z})} > \frac{\alpha(\bar{z})\varphi(\bar{z})\varphi^*(\bar{z}) - \varphi(\bar{z})\alpha(\bar{z})\varphi^*(\bar{z})}{\varphi^*(\bar{z})} = 0.$$

Using this inequality, it is straightforward to show that $D^* > D^{*a}$.

Finally, consider world pollution.[25] Define $r = 1/\gamma$, and $f(z) = [\theta(z)/\varphi(z)]^r + [\theta^*(z)/\varphi^*(z)]^r - 2[\theta(z) + \theta^*(z)]^r$. Summing (A11) and (A12), we see that proving that world pollution goes up is equiva-

25. We are grateful to Michele Piccione and Guofu Tan for help with this proof.

lent to showing that $f(\bar{z}) > 0$ for $\bar{z} > \hat{z}$, where, from (13), $\hat{z}$ is defined by

$$\text{(A13)} \qquad [\theta^*(\hat{z})/\theta(\hat{z})]^{1-r}[\varphi^*(\hat{z})/\varphi(\hat{z})]^r = 1.$$

Using (A8) and (A9), one can show that f is increasing in z. Hence to prove our result, we need only show that

$$\text{(A14)} \qquad f(\hat{z}) \geq 0.$$

Using (A13) to eliminate φ^*, (A14) is equivalent to (where unless otherwise indicated, all functions are evaluated at $\hat{z}$):

$$\text{(A15)} \qquad (\theta + \theta^*)/\varphi^r\theta^{1-r} \geq 2(\theta + \theta^*)^r.$$

Rearranging (A15) yields

$$\text{(A16)} \qquad (1 + \theta^*/\theta)^{1-r} \geq 2\varphi^r.$$

Using (A13) to eliminate θ^*/θ, (A16) is equivalent to

$$\text{(A17)} \qquad \varphi^{*s} + \varphi^s \geq 2\varphi^s\varphi^{*s},$$

where $s \equiv r/(1 - r)$. Hence to show (A14), we must establish (A17). But since $\varphi^{*s} + \varphi^s - 2\varphi^{s/2}\varphi^{*s/2} = [\varphi^{s/2} - \varphi^{*s/2}]^2 \geq 0$, and since $s \geq 0$, we have

$$\varphi^{*s} + \varphi^s \geq 2\varphi^{s/2}\varphi^{*s/2} \geq 2\varphi^s\varphi^{*s},$$

where the latter inequality follows since $\varphi^s\varphi^{*s} < 1$.

QED

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