Eastern Economic Journal, Volume XVII, No.3, July-September 1991

Global Pollution: A Heckscher-Ohlin-Samuelson Model of Pigouvian Taxation

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INTRODUCTION

When emissions from one country adversely affect the environment of other countries, it would be first-best from a "cosmopolitan point of view," write Baumol and Oates [1988, p.266], for the polluting country to impose "an internationally optimal Pigouvian tax on its emissions—a tax equal to marginal damage in all countries together." In the specific case in which "many nations pollute a common resource which they all use equally, such as a border lake," Ruff [1976, p.9] favors a solution in which the nations ". . . agree on a common effluent charge imposed on all their individual polluters, the revenues to go into a common fund which is then distributed back to the member governments on the basis of some predetermined formula." The fund is a ". . . useful device," Ruff [1976, p.9] explains, "for buying the agreement of reluctant nations." Such reluctance is likely, according to Baumol and Oates [1988, p. 278–9], because ". . . we can hardly expect a polluting nation to place a tax on its own polluting industries in order to reduce the damages accruing outside its borders." For that reason Segerson [1985, p.84] concludes that the Pigouvian approach ". . . requires the existence of an international overseeing body with the authority to tax the polluting country for the benefit of society as a whole."

It is not clear in the above literature which particular countries, those that pollute more or those that pollute less, are the "reluctant nations" likely to be made worse off by the uniform Pigouvian tax on emissions and whose agreement would have to be purchased. However, it could be inferred that the less polluting countries would be the net beneficiaries of a program that reduces their exposure to an international level of pollution of which their own emissions are a relatively small portion. This paper uses the well known Heckscher-Ohlin-Samuelson model of international trade to illustrate the case in which the reverse could be true; the pollution intensive countries are beneficiaries of uniform Pigouvian taxation whereas the less polluting countries are made worse off.

In the Heckscher-Ohlin-Samuelson setting there are two countries (which may also be interpreted as one country and the rest of the world), each of which uses the same constant-returns-to-scale technology to produce the same two goods. In the present application of this model, it is assumed that one of these two industries emits pollution that contributes to a common global pollutant level to which all inhabitants of the planet are equally vulnerable.[1] It is also assumed that the global pollution level adversely affects utility levels, as in the models of Pethig [1976], Berglas [1977] and Asaka [1979].

In the Heckscher-Ohlin-Samuelson model, countries differ in their relative factor endowments so that each produces a larger proportion of the good that is intensive in the input in which it has relative abundance. In this paper the marginal conditions are determined for optimal production and distribution; these conditions can be achieved by perfectly competitive markets in the two countries, augmented by a uniform Pigouvian tax and efficient terms of trade. Some numerical simulations are made to compare the utility levels of the two countries in the case in which pollution damage is not internalized

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I am grateful to the anonymous referees for their suggestions for improving this paper and to David E. Ault for sharing with me his insights on international trade and pollution. Any errors that remain are entirely my own.

with the utility levels in those same countries in the case in which the pollution damage is internalized by a Pigouvian tax, with each country's tax revenue redistributed in lump sums to its own citizens. To exclude the possibility of bargaining over terms of trade, which would make the above comparison of utility levels ambiguous, it is assumed that both countries have identical, homothetic utility functions. In this special case, which Layard and Walters [1978, p.114] call the "strong version" of the Heckscher-Ohlin-Samuelson model, there is a unique global allocation in the absence of Pigouvian taxation and a corresponding unique allocation with taxation.

In this "strong version" of the Heckscher-Ohlin-Samuelson model of international trade, the Pigouvian tax increases the relative price of the polluting good, thereby improving the terms of trade for the country that produces relatively more of the polluting good. The intensely polluting country is always better off under global Pigouvian taxation than it would be in the absence of taxation, whereas the relatively less polluting country may be worse off. This result is consistent with the observation that it is primarily the more polluting, industrialized nations that are experimenting with Pigouvian schemes (see Hahn [1989, pp. 104–107]) and with evidence from Leonard [1988, p.117] that less polluting but rapidly developing nations have "... operated on the assumption that their overall industrial development will be enhanced by maintenance of lax environmental standards."

The implication of this paper is that financial support should be given to developing countries to enlist their cooperation in the most effective ways of reducing threats to what Cleveland [1990] calls "the global commons." Such cooperation is essential for, as Dorfman [1988, p.205] warns, "... the really ominous environmental dangers are no longer the local environmental impairments, such as urban smog or stream pollution, that gave the initial impetus to the environmental movements, but threats to the viability of the global environment that are so widespread that no single nation can control them."

OPTIMAL LEVEL OF GLOBAL POLLUTION

Assume that there are two countries, 1 and 2, in the world and two goods, X and Y. Country 1 uses L_{X1} units of labor and K_{X1} units of capital to produce X_1 and country 2 uses L_{X2} and K_{X2} to produce X_2. Likewise L_{Y1} and K_{Y1} in country 1 and L_{Y2} and K_{Y2} in country 2 are used to produce Y_1 and Y_2. The respective national output levels are

$$X_1 = X(L_{X1}, K_{X1}), \qquad X_2 = X(L_{X2}, K_{X2}) \tag{1}$$

$$Y_1 = Y(L_{Y1}, K_{Y1}), \qquad Y_2 = Y(L_{Y2}, K_{Y2}) \tag{2}$$

where the industry production functions are linearly homogeneous.[2]

It is assumed that the production of good X is irreversibly labor-intensive relative to that of good Y. It is also assumed that the global pollution level, e, is proportional to the total output of good Y,

$$e = E[Y_1] + E[Y_2] = E[Y_1 + Y_2], \tag{3}$$

where E is a fixed emission factor that converts units of production into units of pollutant concentration. (The assumption that pollution and output levels are proportional is commonly made in empirical as well as theoretical models of pollution control. See Kohn [1978, pp.38–65].) There are fixed totals of L_1 and K_1 units of labor and capital inputs in country 1 and L_2 and K_2 units in country 2. These inputs are mobile between industries in the same country but are immobile between countries. Goods are costlessly traded between countries, with x_1 and y_1 ultimately consumed in country 1, and x_2 and y_2 in country 2.

Welfare in the two countries is measured by community utility functions,

$$U_1 = U_1(x_1, y_1, e), \qquad U_2 = U_2(x_2, y_2, e) \tag{4}$$

The marginal conditions for international efficiency when each country produces some of both goods and there is costless trade between them, are derived from the following Lagrangian,

$$\begin{aligned} \pounds = {} & U_1(x_1, y_1, E[Y_1 + Y_2]) + \lambda[U_2^0 - U_2(x_2, y_2, E[Y_1 + Y_2])] \\ & + \mu[x_1 + x_2 - X(L_{X1}, K_{X1}) - X(L_{X2}, K_{X2})] + \theta[y_1 + y_2 - Y(L_{Y1}, K_{Y1}) - Y(L_{Y2}, K_{Y2})] \\ & + \alpha[L_1 - L_{X1} - L_{Y1}] + \beta[K_1 - K_{X1} - K_{Y1}] + \gamma[L_2 - L_{X2} - L_{Y2}] + \delta[K_2 - K_{X2} - K_{Y2}], \end{aligned} \tag{5}$$

where U_2^0 is an arbitrary constant. (For convenience, parentheses are used in this paper to denote functions and square brackets multiplication.) Setting the derivatives of $\mathscr{L}$ with respect to the x_i, y_i, L_{Xi}, K_{Xi}, L_{Yi}, and K_{Yi} equal to zero and eliminating the Lagrangian multipliers yields,

$$U_1^y/U_1^x = U_2^y/U_2^x = X^{L_{Xi}}/Y^{L_{Yi}} - [U_1^e/U_1^x + U_2^e/U_2^x]E = X^{K_{Xi}}/Y^{K_{Yi}} - [U_1^e/U_1^x + U_2^e/U_2^x]E \tag{6}$$

This is the condition that trade equalizes the marginal rates of substitution in consumption, while efficient allocation of inputs within each country equates the respective marginal rates of transformation to the common marginal rate of substitution. The marginal rate of transformation, $\partial X_i/\partial Y_i$, which is expressed above in terms of labor and then of capital, is the conventional ratio of marginal products (which equals the additional production of good X in either country when, by transferring inputs between the two industries, the output of Y is reduced by one unit) augmented by the quantities of good X that both countries together are willing to give up to reduce global pollution by E units.[3]

It follows from (6) that

$$X^{L_{Xi}}/X^{K_{Xi}} = Y^{L_{Yi}}/Y^{K_{Yi}}, \tag{7}$$

which is the equality of marginal rates of technical substitution of capital for labor in each industry in each country. Because production technologies are identical and linearly homogeneous in both countries in a Heckscher-Ohlin-Samuelson model of international trade, it follows (see Samuelson [1949, p. 189]) that "real factor prices must be the same in both countries" as must factor proportions in the corresponding industries. In terms of the present model, this implies for the marginal products,

$$X^{L_{X1}} = X^{L_{X2}}, \qquad X^{K_{X1}} = X^{K_{X2}}, \qquad Y^{L_{Y1}} = Y^{L_{Y2}}, \qquad Y^{K_{Y1}} = Y^{K_{Y2}} \tag{8}$$

and for the labor-to-capital ratios,

$$L_{X1}/K_{X1} = L_{X2}/K_{X2}, \qquad L_{Y1}/K_{Y1} = L_{Y2}/K_{Y2}. \tag{9}$$

Corresponding to the efficient allocation is an optimal level of global pollution, e.

EFFICIENT ALLOCATION BY PERFECT COMPETITION, PIGOUVIAN TAXATION AND TRADE

In the "strong version" of the Heckscher-Ohlin-Samuelson model, in which the community utility functions with respect to goods, x and y, are identical and homothetic, there is a unique set of efficient relative prices and terms of trade. Assuming that there are competitive market economies in both countries and that the wage rates in units of the respective currencies are w_1 and w_2, the market price of good x in each country's currency is equal to marginal cost, that is

$$P_{Xi} = w_i/X^{L_{Xi}} \tag{10}$$

If each country imposes the Baumol and Oates' [1988, p.266] "tax equal to marginal damage in all countries together" upon emissions of polluting firms within their borders, that tax is

$$t_i = -[U_1^e/U_1^x + U_2^e/U_2^x]P_{Xi} \tag{11}$$

The revenue from the tax in country i, which is t_iEY_i, is redistributed in lump sums to consumers in that country. The price of good Y will be

$$P_{Yi} = w_i/Y^{LYi} + t_iE \tag{12}$$

In maximizing utility, consumers ignore the fact that one of the goods is polluting (as befits the concept of an externality) and select combinations of the two goods such that the marginal rate of substitution in consumption, U_i^y/U_i^x, equals the ratio of market prices, P_{Yi}/P_{Xi}. Substituting (10), (11) and (12) for the price ratio confirms that the marginal condition for overall efficiency, (6), is satisfied.

Each country produces a relatively large quantity of the good whose production is intensive in the input that is relatively abundant within its borders. Given that good Y is the capital intensive good, and assuming that, say, L_1/K_1 is greater than L_2/K_2, it follows that X_1/Y_1 will exceed X_2/Y_2. In this "strong version" of the Heckscher-Ohlin-Samuelson model, country 1 trades $[X_1\text{-}x_1]$ to country 2 in exchange for $[Y_2\text{-}y_2]$.

Equilibrium in the balance of trade requires that the value of exports equals the value of imports,

$$P_{Xi}[X_1 - x_1] = P_{Yi}[Y_2 - y_2], \tag{13}$$

and it follows that

$$[X_1 - x_1]/[Y_2 - y_2] = U_i^y/U_i^x \tag{14}$$

In the Heckscher-Ohlin-Samuelson model of international trade, P_{X1} and P_{X2} as well as P_{Y1} and P_{Y2} each represent in their own currencies the same amount of real buying power. This also holds for the respective wage rates. It also follows that the Pigouvian tax in real terms will be the same in both countries. If a different tax were imposed in each country, this would, as McGuire [1982, pp.350–1] emphasizes, destroy factor price equalization and the Heckscher-Ohlin-Samuelson model would no longer be applicable.

A NUMERICAL SIMULATION

The "strong version" of the Heckscher-Ohlin-Samuelson model is useful for simulating production and trade between the two countries before and after Pigouvian taxation. Linear homogeneous production functions are assumed for each industry and the common utility function is taken to be

$$U_i = [\ln (x_i) + \ln (y_i)]/[1 + \Omega_i e] \tag{15}$$

Observe that in this formulation of the utility function, the weights Ω_i can be different for the two countries without violating the strong Heckscher-Ohlin-Samuelson condition that the marginal rate of substitution of good y for good x is the same in each country as long as the ratio, y_i/x_i, is the same.[4] In this simulation model, it is nevertheless assumed that preferences for environmental quality are the same in the two countries and that $\Omega_1 = \Omega_2 = 1$. Any *qualitatively* different result that can be obtained for $\Omega_1 \neq \Omega_2$ can also be obtained with appropriate values of $\Omega_1 = \Omega_2$.

The numerical results of the simulation are contained in Table 1. Without the tax, the consumers' marginal rate of substitution of good X for good Y (see row 14) equals both the terms of trade (rows 10 and 11) and the corresponding ratio of like marginal products (row 8). However, this is not an efficient solution; it is possible, by producing more X and less Y and reallocating outputs, to make both countries better off.

With the Pigouvian tax, the common marginal rate of substitution in consumption (row 14) equals both the terms of trade (rows 10 and 11) and the sum of the ratio of like marginal products (row 8) plus the combined marginal willingness to pay (row 9), measured in units of X, to reduce the pollution associated with the marginal unit of Y. Because pollution damage is internalized, the marginal rates of substitution, trade, and transformation of good X for good Y are higher under the efficient allocation than under the inefficient allocation. More of good X and less of good Y is produced in both countries (rows 4 and 7) and the global pollution level (row 15) is lower.

TABLE 1.
Solutions of a Numerical Example of A Strong Version of the Heckscher-Ohlin-Samuelson Model with and without a Pigouvian Tax*

Without the Tax	With the Tax
1. $U_1 = 30.0187; U_2 = 30.2847$	$U_1 = 29.9480; U_2 = 30.3501$
2. $L_{X1} = 14000.0; L_{Y1} = 1000.00$	$L_{X1} = 14206.1; L_{Y1} = 793.955$
3. $K_{X1} = 7200.00; K_{Y1} = 2800.00$	$K_{X1} = 7667.06; K_{Y1} = 2332.95$
4. $X_1 = 11346000; Y_1 = 529558$	$X_1 = 11680820; Y_1 = 434885$
5. $L_{X2} = 3500.00; L_{Y2} = 6500.00$	$L_{X2} = 3912.09; L_{Y2} = 6087.91$
6. $K_{X2} = 1800.00; K_{Y2} = 18200.00$	$K_{X2} = 2111.37; K_{Y2} = 17888.6$
7. $X_2 = 2836500; Y_2 = 3442130$	$X_2 = 3216690; Y_2 = 3334630$
8. $X^{LXi}/Y^{LYi} = X^{KXi}/Y^{KYi} = 3.5709$	$X^{LXi}/Y^{LYi} = X^{KXi}/Y^{KYi} = 3.5027$
9.	$- [U_1^e/U_1^x + U_2^e/U_2^x]E = 0.44945$
10. $(X_1 - x_1)/(y_1 - Y_1) = 3.5709$	$(X_1 - x_1)/(y_1 - Y_1) = 3.9521$
11. $(x_2 - X_2)/(Y_2 - y_2) = 3.5709$	$(x_2 - X_2)/(Y_2 - y_2) = 3.9521$
12. $x_1 = 6618500; y_1 = 1853450$	$x_1 = 6699770; y_1 = 1695240$
13. $x_2 = 7564000; y_2 = 2118230$	$x_2 = 8197740; y_2 = 2074270$
14. $U_1^y/U_1^x = U_2^y/U_2^x = 3.5709$	$U_1^y/U_1^x = U_2^y/U_2^x = 3.9521$
15. $e = 0.00397169$	$e = 0.00376951$

*The industry production functions are $X = 720[24^{.1}] [L_X]^{.7} [K_X]^{.3}$ and $Y = 180 [36^{.1}] [L_Y]^{.3} [K_Y]^{.7}$, the emission factor is $E = 10^{-9}$, the common utility function is $U_i = [\ln (x_i) + \ln (y_i)]/[1 + e]$, and the resource constraints are $L_1 = 15000$, $K_1 = 10000$, $L_2 = 10000$ and $K_2 = 20000$. The competitive market equilibrium with trade is modeled by reducing the world economic system to three independent variables and, by an iterative search routine, finding the values of these variables that satisfy the remaining marginal conditions. A computer printout is available upon request.

Country 2, whose production is relatively intense in the polluting good, is better off under Pigouvian taxation (row 1) because the terms of trade are more favorable for that good. Although world demand for the polluting good is down, production of that good in country 2 is reduced by a comparatively small amount (row 7). Country 2 not only receives more of good X for its exports of Y (see row 11) but produces more of its own X (see row 7) and also benefits from the reduction in global pollution. In the absence of a redistribution of Pigouvian tax revenue from country 2 to country 1, the latter is worse off under the Pigouvian tax because the benefit of improved environmental quality is more than offset by the deteriorated terms of trade for the nonpolluting good.

Although the change in relative price caused by the Pigouvian tax always makes the more polluting country better off in this model, it does not necessarily follow that the less polluting country is always worse off. The case in which both countries are made better off by Pigouvian taxation is modelled by intensifying the aversion to pollution by setting $\Omega_1 = \Omega_2 = 100$. Although the same qualitative result can be obtained by increasing Ω_1 alone, it is useful to show that the two sets of possible outcomes with this model are consistent with the assumption of identical preferences.

The simulation model in Table 1, in which the less polluting country is made worse off by Pigouvian taxation is presented here as the more realistic case. The results in this case are consistent with empirical evidence reported by Hahn [1989] that it is predominantly the industrialized countries of the world that are adopting Pigouvian schemes and with data released by the Global Environmental Monitoring System of the World Health Organization [1989, pp.10, 11, 27, 28] which confirm that the developing countries of the world are lagging in pollution control.

CONCLUDING REMARKS

In the case in which countries contribute to and suffer from a common level of global pollution, intuition may suggest that a uniform Pigouvian tax on emissions, in the absence of redistributions of tax revenue between countries, would be more likely to reduce the welfare of more polluting countries than of less polluting countries. This paper uses a "strong version" of the Heckscher-Ohlin-Samuelson model of international trade to demonstrate that the opposite result, which in fact is consistent with certain empirical observations, may hold.

It should be emphasized that the results of this paper are based on strong assumptions. Because preferences are homothetic in goods x and y in the "strong version" of the Heckscher-Ohlin-Samuelson model,

$$U^y/U^x = \alpha X/Y = P_y/P_x, \quad (16)$$

where α is a constant (see Layard and Walters [1978, p.160]). It follows, by substituting (16) into an income constraint to derive a market demand curve, that the price elasticity of demand and the income elasticity of demand for both goods are unity. This rules out the possibility of strong price or income effects that could drastically reduce overall demand for the polluting good and thereby reverse the results of this paper.

Indeed, it is possible that a different model would yield contrary conclusions. Merrifield [1988, p. 277], for example, finds that more stringent pollution control standards for reducing acid rain would benefit the less polluting country, Canada, rather than the more polluting United States. Although Merrifield's model is also a general equilibrium model, each country produces a different composite good, has some price-setting power, and his result is strongly affected by a movement of capital between the two countries. Merrifield's model also includes abatement capability whereas in the present model, emissions are a rigid function of the levels of output.[5]

What should finally be emphasized in the simple approach used in this paper is that the interest of industrialized countries in Pigouvian schemes and the greater resistance of developing countries to pollution control can be predicted with a model in which preferences in the two types of countries are identical. There is no need to explain the behavior of developing countries in terms of a greater toleration for pollution, as in Siebert [1981, p.132], or slowness to evolve an environmental awareness, as in Hepinstall [1985] and Ting and Jou [1988]), or professed "unused assimilative capacities for natural disposal of wastes," as in Leonard [1988, p.120]. While such motivations may exist, the argument for compensating developing countries for their cooperation in controlling global pollution is based in this model on balance-of-trade considerations alone.

NOTES

1. This assumption has precedence in the "pure international public bad" in Markusen [1975, p.17] and the "transnational pollutant flow" in Merrifield [1988, pp.266–7]. That international emissions would generate a uniform level of global pollution is a strong assumption but some suggestive examples are: fugitive pesticide emissions whose toxic residues spread throughout the world; the accumulation of carbon dioxide emissions and the consequent rise in mean world temperature; the impact of chlorofluorocarbon emissions on the earth's protective ozone shield; chemical transformation of sulfur and nitrogen oxide emissions in the atmosphere causing acid rain: and ocean dumping of toxic wastes that destroy fisheries and undermine the oxygen-producing photosynthetic activity of the sea. For a taxonomy of environmental ". . . problems that physically involve all or nearly all nations of the world, either as contributing parties (emitters) or damaged parties (receptors) or both," see Russell and Landsberg [1971].
2. These industry production functions are derived from homothetic, increasing- then decreasing-returns-to-scale, production functions of firms. For example, if in both of the industries there are a continuously variable number of firms, each using a production function such as

$$x = 792[l_x]^{.8}[k_x]^{.4} - 3[l_x]^{1.8}[k_x]^{1.4} \text{ and}$$
$$y = 198[l_y]^{.4}[k_y]^{.8} - [l_y]^{1.4}[k_y]^{1.8}/2,$$

the industry production functions will then be

$$X = 720[24^{.1}][L_x]^{.7}[K_x]^{.3} \text{ and}$$
$$Y = 180[36^{.1}][L_y]^{.3}[K_y]^{.7}.$$

The mathematics for these aggregations, which are used in Table 1 of this paper, are described in Kohn [1988].

3. In this model the global pollution level is an international version of a Samuelson [1954] "pure public bad." For some illustrative calculations of marginal willingness to pay by entire nations to prevent the deterioration of "a global common property resource," see D'Arge [1976, p.268].
4. In their study of a tax on greenhouse gases, Kosobud and Daly [1984] find that the less polluting "Latin American Country" is not damaged by global climatic change whereas the more polluting, "North American Country" is. In the context of the present model, this implies different values of Ω for each country.
5. The incorporation of abatement in the Heckscher-Ohlin-Samuelson model, perhaps in the format suggested by Harford [1989], would be a useful extension for the next stage of this research. This would greatly complicate the analysis for it would have to begin with the production function of individual polluting firms rather than industries. At a minimum, this would more than double the number of variables in the iterative search routine used to solve the simulation model. However, it is not expected that abatement capability would reverse the results obtained with the present model.

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