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Embodied Pollution and Trade: A Two-Country General Equilibrium Model

Xinshen Diao and Terry L. Roe*

The effects of environmental policy on trade and social welfare are analyzed in a modified Heckscher-Ohlin framework where pollution is embodied in a good consumed. Utility is non-homothetic to account for changes in the demand for healthy goods when income increases. If the polluting input is used intensively, taxing it alone can cause an increase in the good's level of pollution concentration. Instead, a tax on the polluting input in combination with a subsidy to the non-polluting input can result in Pareto improvement. Contrary to other approaches, an abatement policy does not necessarily have a negative effect on a country's comparative advantage. However, if the country is large, change in terms of trade may cause one country to be made better off at the expense of the other, which suggests that compensatory payments may be required to encourage abatement policies.

I. Introduction

Environmental effects on health and the gains from North-South trade are modeled by adapting the traditional Heckscher-Ohlin framework to account for pollution generated from production, becoming embodied in goods and affecting health through consumption. As incomes grow, a greater proportion of income is spent on health including expenditures to mitigate environmental effects (World Bank (1993),4). Consequently, health has become an important impetus for environmental protection in wealthy countries as negotiations over sanitary, phyto-sanitary and ISIO 9000 standards suggest. Agricultural pollutants that enter the food chain have received considerable attention in the U.S. (Caswell (1991)). U.S. Epidemiological evidence suggests that 2-3 percent of all cancers associated with environmental pollution occurs from exposure to pesticide residues in food stuffs which may present a greater risk than hazardous waste. Another estimate is that of all enteric diseases reported in the United States, food-born disease constitutes one-third of total cases annually (Archer and Young (1988)). Further, environmental effects on health in low income countries are a major cause of morbidity and mortality. For example, a study jointly sponsored by the World Health Organization and the World Bank and summarized by Murray and Lopez (1997) finds that adults under the age of 70 in Sub-Saharan Africa today face a higher probability of death from noncommunicable disease, (of which diarrhial ranks 4th) than adults of the same age in the established market economies.

As rich countries tend to be more willing to pursue policies that alleviate negative environmental impacts than are poor countries, concern has been expressed about the possible effects of these

* Research Associate and Professor, respectively, Department of Applied Economics, University of Minnesota, 1994 Buford Ave., St. Paul, MN 55108. Funding was provided by the Macro Economic Policy Team under a USAID/MUCIA Environmental and Natural Resources Policy and Training Project.

policies on trade and welfare of countries in the South. The conflicts and potential for conflict between trade and environmental policies, especially the effects of environmental protection on comparative advantage and gains from trade[1], have become a North-South issue.

Most of the trade-based models tend to predict that more stringent abatement policies negatively affect countries' comparative advantage, thus inducing pollution intensive industries to migrate to the South, where environmental standards are more lax. Pethig (1976) and Siebert (1979) were among the first to focus on pollution's effect on productivity in a trade context. After accounting for the externality, comparative advantage is found to lie with the country whose shadow price for pollution is low relative to the other country. In a continuum good model, Copeland and Taylor (1994) find that a higher income country tends to choose stronger environmental protection, and to specialize in relatively clean goods. Other contributions focusing on the resource productivity effects are those of McGuire (1982), and Merrifield (1980). The former used a Heckscher-Ohlin framework to obtain more general results than the previous studies, while the latter considered international capital mobility and the likelihood of that polluting industries in some countries could close. Chichilinisky (1993) studies in an innovative way the effect of property rights on comparative advantage in the presence of a potentially exhaustible resource and obtains a similar result, namely, the countries in which property rights for the environmental resource are poorly defined tend to export environmentally intensive goods.

The models upon which these results are based tend to treat pollution proportionate to output (Siebert (1979) and Kohn (1991)), or to be an input into the production process (Pethig (1976), McGuire (1982), Merrifield (1989) and Copeland (1984)). However, inputs used in the production process typically yield a pollution by-product, which is not necessarily proportional to output, nor is pollution typically an input per se. Moreover, some forms of pollution affect health or utility through consumption of market goods. The health effects through consumption have direct trade implications if the pollutants are *embodied* in the good.

The approach developed here treats pollutants as a by-product of the inputs employed in the production process. Pollutants become *embodied* in the goods produced, and affect health and utility though consumption. To emphasize the North-South health-pollution-trade linkages, identical but non-homothetic preferences are assumed so that the richer North consumes a higher level of the healthy goods than the South. We find that the first best policy instrument is not only a tax on the polluting input, but also a subsidy on the non-polluting input if the input is intensively used. We analyze the effects of pollution abating instruments on trade and welfare for both the small and large country assumptions, and find that pollution abatement does not necessarily have an adverse effect on the country's comparative advantage. Hence, a country's comparative advantage in trade is still determined by factor proportion theory (the Heckscher-Ohlin theorem). Further, the positive effect of Pigouvian taxes on a single country's welfare can be undone when the indirect effect of these taxes cause the terms of trade between North and South to adjust. This result suggests that compensatory payments between North and South may be necessary to obtain trade agreements.

The basic model is laid out in Section II. The Pareto optimal solution is analyzed in Section III. Section IV focuses on the internalization of the externality and a number of propositions.

1. See Patrick Low (1992) for a review of this literature.

In Section V we develop a numerical example to further clarify the conceptual model and its implications. The numerical example also serves to illustrate the nature of a number of analytical predictions that are indeterminate.

II. The Basic Model

There are two open economies, North and South, in which two tradable goods, X_1 and X_2 are produced by two inputs, V_1 and V_2. The inputs are mobile between sectors, but immobile across countries. The North is wealthier than the South by being endowed with more V_2 and equal amounts of V_1. Other important departures from the Heckscher-Ohlin 2×2×2 model are the assumptions: (1) Pollution is a by-product of the production of X_1 and is *embodied* in X_1; (2) Two countries have identical but non-homothetic preferences over goods and pollution. In most of the literature, the health effects of pollution are modeled through the environmental degradation. However, many pollutants are embodied in the goods when polluting inputs, such as pesticides, herbicides and growth hormones, are used to produce them. The first assumption captures this phenomenon by associating pollution with an input of production, which in turn becomes embodied in output as contaminants. The contaminants negatively affect health through the consumption of the good. The second assumption allows us to capture the phenomenon that demand for a more pollution-free good increases in greater proportion to an increase in income.

The production, pollution and utility functions are specified as follows.

1. Production Technologies

$$X_1^i = F(V_{11}^i, V_{21}^i), \qquad X_2^i = G(V_{12}^i, V_{22}^i),$$

where V_{fj}^i denotes input V_f allocated to the production of the j-th commodity in the i-th country. The technologies are strictly increasing, concave, continuously differentiable and homogeneous of degree one in arguments, and are identical across countries.

2. Pollution

Pollution embodied in a good is generated by an input used in the production of that good. The same input employed in the production of a different good may not exhibit an embodied externality. For example, chemicals used to produce synthetic fabrics in general have no embodied effect, while chemicals used in food processing do. We denote the input which generates pollution as input V_2, and the good in which pollution is embodied as X_1. Output of X_1 can be viewed as an agricultural good, while pollution is chemical residues from the use of fertilizers, pesticides, or toxins and bacteriological contaminants from the lack of sufficient use of non-polluting inputs such as adequate refrigeration. The amount of *embodied* pollution per unit of good, i.e., its concentration, depends on the amount of the input (V_2 in this case) used *per unit* of the good produced. That is, the contaminant level of the embodied pollution is not affected by the scale of the production of X_1. To satisfy this scale neutral property, the embodied pollution can be defined as a function of V_{21}/X_1, i.e., it depends on the amount of V_2 used in per unit of X_1. Since the technology of X_1 is homogeneous of degree one, V_{21}/X_1 can be replaced by V_{21}/V_{11}, which implies that the pollution generation function is homogenous of degree zero in (V_1, V_2):

$$po^i = f(V_{21}{}^i/V_{11}{}^i).$$

This implies that pollution per unit of output is increasing in input V_2 (e.g., pesticides) but decreasing in V_1, a non-polluting input (e.g., labor or capital). Consequently, the level of contamination is determined by *relative* input levels. In this case, pollution is a by-product of producers' efforts to produce the good X_1.

3. Utility

Several considerations affect the specification of utility. Following the Heckscher-Ohlin model, the specification should permit identical preferences among agents in the North and the South. Preferences should be consistent with the observation that the North consumes higher levels of healthy goods relative to other normal goods than the South. Thus, while utility functions are identical, different income levels permit the North prefer to consume healthier foods than the South. These considerations are easily handled by specifying a quasi-homothetic form of utility (e.g., Gorman polar form, Gorman (1953); or a Stone-Geary form[2]). As pollution is *embodied*, it affects health through *consumption* which maps into utility. Examples, as mentioned, are organic and inorganic impurities in food tissues, such as bacteria and bacteriological toxins, pesticides, herbicides and heavy metal deposits. Following the health production function literature, health, an argument in the utility function, is itself treated as a function of the goods consumed. Hence, we define a composite utility function whose arguments are a good X_1 (such as food) whose purity level can vary, and a non-polluted good X_2 (such as all other non-ingestible goods):

$$U_i = U(E_iX_{1i},\ X_{2i}),$$

where E_i describes the purity per unit of good X_1. The utility level of X_1 consumed is affected by its purity, E, which is negatively affected by the embodied pollution, i.e.,:

$$E = E(po),\ \text{and}\ E' < 0.$$

X_1 reaches its purest level when $E_i = 1$. As the purity of X_1 cannot be chosen by consumers, E is an externality for consumers. Since firms in the both regions are assumed to employ the same technology, the level of pollution embodied in X_1 is the same only if the two regions face the same input prices. However, if input prices in the two regions are different, then the purity of X_1 consumed in one country may not equal the purity of the X_1 produced there because of

2. It is known that a homothetic utility function, which is widely used in most general equilibrium multi region models, has a constant unitary income elasticity, and cannot allow that demand for health increase relative to other goods. Thus, a non-homothetic utility function has to be chosen..

foreign trade. For the X_1 − exporting country, the pollution embodied in its consumption of X_1 is the same as the pollution embodied in its production of X_1 since in obtains non of the good from another country. Thus, we define the purity of X_1 as a linear function of pollution produced, i.e.,

$$E_i = 1 - po^i, \text{ such that } 0 \leq po^i < 1.$$

For the X_1 − importing country, the level of the purity consumed depends on the weighted average of pollution embodied in the goods produced by domestic and foreign producers. The weighted average is given by:

$$E_h = (1\text{-}po^h)\gamma + (1\text{-}po^j)(1\text{-}\gamma), \ j \neq h,$$

where $\gamma = X_{1h}^h / X_{1h}$ is the ratio of domestic production of X_1 to its total consumption in the X_1 − importing country, and j represents X_1 − exporting country.

4. Equilibrium

Based on the model set up, a competitive general equilibrium is a set of prices (P_{x1}, P_{x2}, w_1, w_2), a commodity bundle $(X^i_1, X^i_2, X_{i1}, X_{i2})_{i=n,s}$, and a set of input allocations $(V_{11}{}^i, V_{12}{}^i, V_{21}{}^i, V_{22}{}^i)_{i=n,s}$, with E_i, the purity of good X_1, such that: (1) all agents treat prices parametrically; (2) producers maximize their profits; (3) consumers maximize their utilities subjecting to their budget constraints, treating the level of pollution as parameter; (4) in each country the demand for the inputs are equal to their endowments; (5) in the world, the demand for each good is equal to the supply of this good. Consequently, the Walrasian equilibrium implies that the level of pollution, (po^i), and hence the quality of X_1, are determined by the equilibrium levels of $V_{21}{}^i/V_{11}{}^i$. By the factor price equalization theorem (Woodland (1982),72), the input prices are equalized across countries. Hence, firms in both countries employed the same level of each input for per unit of output. Since pollution is homogenous of degree zero in V_{21}/V_{11}, it is equalized as well, i.e., $po^n=po^s$. Hence, the purity of X_1 is the same in both countries. Of course, in real economies, this result is not observed, in part, due to country policies.

Given that the North is endowed with more V_2 than the South, if the production of X_1 uses $V_2(V_1)$ intensively, an equilibrium implies that the North exports (imports) X_1, and the South exports (imports) X_2. For a non-homothetic utility function, it is possible to obtain the result that share of income spent on the non-polluted good in the North is larger than in the South. A Stone-Geary form is used in the empirical example to capture this effect.

III. Optimal Analysis with Embodied Pollution

Obviously, since pollution is an externality which affects consumer's utility negatively, the competitive equilibrium is not Pareto optimal. By comparing the necessary conditions for Pareto optimality with those for a competitive equilibrium, we are able to identify first best policy instruments and then to correctly specify the policies to internalize the externality. For a two-country model, the conditions which yield Pareto optimal outcomes for each country cannot be derived separately as the two economies are interdependent. However, by maximizing one country's social welfare function subject to its endowments, and a constraint which requires that the level of the other country's welfare be at least equal to the level derived in the competitive equilibrium, Pareto optimal conditions for the world can be obtained. The problem can be stated as:

$$\max_{(X,V,po)} U((1-po^j)X^j_{1_j}, X_{2_j})$$

$$\text{s.t.}: \ U((1-po^h)X^h_{1_h}+(1-po^j)X^j_{1_h}, X_{2_h}) \geq U^*_h,$$

$$X^j_{1_j} + X^j_{1_h} = F(V_{11_j}, V_{21_j}),$$

$$X^h_{1_h} = F(V_{11_h}, V_{21_h}),$$

$$X_{2_j} + X_{2_h} = G(V_{12_j}, V_{22_j}) + G(V_{12_h}, V_{22_h}),$$

$$po^j = f\left(\frac{V_{21_j}}{V_{11_j}}\right),$$

$$po^h = f\left(\frac{V_{21_h}}{V_{11_h}}\right),$$

$$V^j_{f1} + V^j_{f2} = \overline{V}^j_f,$$

$$V^h_{f1} + V^h_{f2} = \overline{V}^h_f,$$

j = X_1-exporting country, h = X_1-importing country, f = 1, 2.

The rearranged first order conditions characterizing a constrained optimum to this problem (taking the X_1-exporting country as an example) are:

$$\frac{U_{1_i}(1-po^i)}{U_{2_i}} - \frac{G_{1_i}}{F_{1_i}} = \frac{-\lambda^i_e f_{1_i}}{F_{1_i}U_{2_i}},$$
$$\frac{U_{1_i}(1-po^i)}{U_{2_i}} - \frac{G_{2_i}}{F_{2_i}} = \frac{-\lambda^i_e f_{2_i}}{F_{2_i}U_{2_i}}, \tag{1}$$

where $F_f \equiv \partial F/\partial V_f$, $G_f \equiv \partial G/\partial V_f$, $f_f \equiv \partial f/\partial V_f$, $U_i \equiv \partial U/\partial X_i$. λ^j_e is the shadow price of the effect of pollution on utility in the X_1-exporting country; and $\lambda^j_e = -U_{E_j} X^i_{1_j} - \lambda^h_u U_{E_h} X^j_{1_h}$, where $U_{E_j} = \partial U/\partial E_j$. λ^h_u is the shadow price associated with the importing country's utility constraint. The second term in this equation accounts for the marginal effect of embodied pollution on the X_1-importing country's utility from the imports $X^j_{1_h}$. The importing country's shadow price of pollution is $\lambda^h_e = -U_{E_h} X^h_{1_h}$. This result shows that the shadow price of pollution in the X_1-importing country is only associated with contaminants from its own production $X^h_{1_h}$, since as noted above, it does not export this good to the other country. The shadow price of pollution, λ^i_e, is negative, as the marginal utility of purity of X_1, U_{E_i}, is positive. The results of Equation (1) indicate that a competitive equilibrium is not Pareto optimal, since in a competitive equilibrium, the marginal effect of pollution is not taken into consideration, that is λ^j_e and λ^h_e do not appear.

In the pollution sector, the relationship between marginal products of inputs and their shadow prices, adjusted by the shadow price of pollution and marginal products of inputs in the pollution function can be expressed as:

$$F_1/F_2 = (\lambda_1 - \lambda_e f_1)/(\lambda_2 - \lambda_e f_2), \tag{2}$$

where λ_f is the shadow price for V_f. In contrast to a Walrasian equilibrium, the right-hand side of (2) is λ_1/λ_2, which corresponds exactly to the relationship in the clean sector X_2:

$$G_1/G_2 = \lambda_1/\lambda_2.$$

Note that $(\lambda_1 - \lambda_e f_1)/(\lambda_2 - \lambda_e f_2) < \lambda_1/\lambda_2$, as $\lambda_e<0$, $f_1<0$, and $f_2>0$. Since the function $F(\cdot)$ is concave, the policy implication of Equation (2) is to induce sector X_1's producers to use more of V_1 and less of V_2, the polluting input. In this case, the ratio of V_1/V_2 employed in sector X_1 falls relative to the ratio that would otherwise prevail in competitive equilibrium. In the next section, we prove that if sector X_1 uses the polluting input intensively, taxing V_{21} alone cannot achieve this objective.

IV. Policy to Internalize the Externality

The existence of pollution as a negative externality implies that government for each country can potentially improve its country's social welfare by internalizing the externality. As pollution is function of the V_2/V_1 ratio, if producers of X_1 can employ more V_1 to substitute for the polluting input V_2, then the level of contaminants per unit of X_1 can be reduced. Hence, each country's government must induce producers of X_1 to use more V_1 and less V_2 by raising the relative cost of V_2/V_1 employed in X_1. For the small country, this result can be accomplished by a tax on V_{21} and (or) a subsidy to V_{11} to alter the ratio of inputs employed. Of course, in general equilibrium, such policies affect all endogenous variables, including factor returns, production and consumption. If the country is not small, then world prices are also affected. The effects of these policies are delineated in the following propositions.

Let t_i denote a tax rate on V^i_{21} and s_i a subsidy rate on V^i_{11}. The model specified above yields the following results:

Proposition 1: Holding world price constant (a small country), for a given $s_i \geq 0$, if X_1 is $V_2(V_1)$ intensive, a positive ad valorem tax rate t_i on V_{21} in country i affects this country's (a) real unit cost of V_2/V_1 in the polluting industry negatively (positively); (b) supply of X_2 positively and X_1 negatively; (c) GNP (including the net lump sum tax transfer) negatively; and (d) embodied pollution po^i positively (negatively).

See Appendix for proof. Note that for the factor rental ratio and the level of embodied pollution, the impacts of the tax depend on whether the taxed input is used intensively in the polluting industry, while the impacts on the supplies of two goods and GNP are independent of factor intensity. Result (d) also implies that if the polluting industry uses the polluting input intensively, taxing the polluting input alone cannot abate pollution, but instead causes an increase in the level of embodied pollution, po^i. However, if sector X_1 is V_1 intensive, then taxing the polluting input V_{21} leads to Pareto improvement.

Proposition 2: The effects of a subsidy rate s_i on V_{11} are the reverse of results of (a), (b) and (d), and are the same as (c) in Proposition 1.

The proof for Proposition 2 is similar to that of Proposition 1 (see Appendix). As a tax on V_{21} and a subsidy on V_{11} work in the opposite direction for (a), (b), and (d), the joint impacts of the tax and subsidy are difficult to derive analytically. We will demonstrate them with a numerical example in Section VI.

Proposition 3: In the small country case, the country which imports the polluting good benefits from the unilateral action of the exporting country to reduce pollution.

This is an obvious result since the reduction of the pollution embodied in the imported good can improve the importing country's social welfare. Proportion 3 holds for any neoclassical form of the utility function.

In the large country case, the world price must adjust to re-equilibrate excess demand following a country's imposition of an abatement policy. From Proposition 1 and 2, we know that if any country (or both) taxes V_{21} only, the total supply of X_1 falls and X_2 rises; if any country (or both) subsidizes V_{11} only, the total supply of X_1 rises and X_2 falls. However, the joint effects of a tax on V_{21} and a subsidy to V_{11} are indeterminate. The numerical example in Section VI is used to show the nature of this relationship.

Once the small country assumption employed in the derivation of the first two propositions is relaxed, changes in the terms of trade induced by a country's tax or subsidy can make one country better off at the expense of the other. Change in a country's utility from both the tax (and/or subsidy) and the consequent price adjustment is obtained by totally differentiating the indirect utility function:

$$dU_i = (\partial U/\partial GNP_i)(X_1^i - X_{1_i})dP_{X_1} + (\partial U/\partial GNP_i)dGNP|_{\text{given P}} + (\partial U/\partial E_i)[dE_i|_{\text{given s and t}} + dE_i|_{\text{given P}}],$$

where X_1^i - X_{1_i} is positive (negative) for the X_1-exporting (importing) country.

Proposition 4: If the abatement policy causes P_{x1} to rise (fall) and this change does not affect E_i too much, the X_1 – exporting (importing) country is made better off. The X_1 – importing (exporting) country is made worse off, if it does not abate, or if, with an abatement, its trade volume of X_1 is large. The X_1 – importing (exporting) country is better off only when the trade volume of X_1 is small and the positive change in the utility from the abatement effects is large.

Proof: The direct effects of the abatement on a country's utility is

$$(\partial U/\partial GNP_i)dGNP|_{\text{given P}} + (\partial U/\partial E_i)dE_i|_{\text{given P}},$$

which is positive, provided that the tax/subsidy rate is not too high such that the welfare loss caused by the fall in the country's GNP can be compensated by the welfare gain coming from the reduction of the pollution. By the Stolper-Samuelson theorem, and together with Proposition 1, the sign of $(\partial U/\partial E_i)dE_i|_{\text{given t and s}}$ is positive if P_{x1} rises (falls) and X_1 is V_2 (V_1) intensive. Otherwise, it is negative. Hence, dU_i is positive for the X_1 – exporting (importing) country, when dP_{x1} > (<) 0 and (i) X_1 is V_2 (V_1) intensive, or (ii) $dE_i|_{\text{given t and s}}$ is small. When dP_x > 0, the term $(X_1^i - X_{1_i})dP_{X_1} < 0$ for the X_1 – importing country. Also, dU_i < 0 is possible, if (i) this country does not abate, or (ii) $dE_i|_{\text{given t and s}}$ is small. Likewise, we can prove that when dP_{x1} <0, the X_1 – exporting country is worse off. When the trade volume is small, a X_1 – importing (exporting) country can be made better off when P_{X_1} rises (falls), provided that the positive abatement effects of the optimal policy on its utility is large.

In summary, and in contrast to the analysis in Section III, a country can be made worse off when its government's abatement policy causes the terms of trade to change in favor of the other country. One country is made better off from two effects, one of which is from a fall in pollution, the other is from an improvement in its terms of trade. The other country can be made worse off because the welfare gain from a fall in pollution is smaller than the welfare loss from the worsening of its terms of trade. Hence, a Pareto optimal outcome can only be realized if the country that is made better off compensates the country made worse off.

The implications of this result suggests that in the absence of international transfers from the country made better off to the country made worse off, the worse-off country is unlikely to adopt an abatement policy. Moreover, countries that experience welfare gains from abatement policy which also improves their terms of trade, may be encouraged to adopt an over-taxing or over-subsidizing policy if the incremental losses from over-taxing (subsidizing) are smaller than the gains from changes in the terms of trade. For these countries, abatement can serve as an excuse to turn the terms of trade in their favor.

V. An Example Economy

In order to further clarify the conceptual model and its implication, a numerical example is developed in this section. Production functions are Cobb-Douglas, utility functions are of Stone-Geary form. The embodied pollution, *po*, is proportional to the input ratio in sector X_1. To illustrate the proposition, it is necessary to consider two alternative states of the world. Alternative A is a case where the North exports X_1 and X_1 is V_2 intensive. Alternative B is a case where the North imports X_1 and X_1 is V_1 intensive. With assumed parameters, the production, utility, and pollution functions, and the levels of factor endowments in each country are given as follows:

$$V_1^n=V_1^s=10,\ V_2^n=18,\ V_2^s=12,$$

$$po^i=0.02(V_{21i}/V_{11i}),$$

$$U_i=((1-po^i)X_{1i}-1)^{0.4}(X_{2i}-1)^{0.6},\ \text{for } X_1-\text{exporting country},$$

$$U_h=((1-po^h)X_{1h}{}^h+(1-po^i)X_{1h}{}^i-1)^{0.4}(X_{2h}-1)^{0.6},\ \text{for } X_1-\text{importing country}.$$

The technology corresponding to Alternatives A and B are:

Alternative A: North Exports X_1, and X_1 is V_2 intensive

$$X_1=V_{11}{}^{0.25}V_{21}{}^{0.75},$$

$$X_2=V_{12}{}^{0.75}V_{22}{}^{0.25};$$

Alternative B: North Imports X_1, and X_1 is V_1 intensive

$$X_1=V_{11}{}^{0.75}V_{21}{}^{0.25},$$

$$X_2=V_{12}{}^{0.25}V_{22}{}^{0.75}.$$

Under Alternative A (B), the North exports (imports) X_1, while the South imports (exports) X_1. As a benchmark, a Walrasian equilibrium with no abatement policy is calculated for each alternative. These benchmark results are then served as a numeraire to contrast the results of policy simulations. Five equilibria for both the small and large country cases are calculated. The optimal levels of tax rate, t, and subsidy rate, s, are calculated from the social planner's problem:

$s=\lambda_e f_1/\lambda_1$,

$t=-\lambda_e f_2/\lambda_2$.

The results of the tax and subsidy rates are:

t_i=0.0767, s_i=0.1493 for Alternative A;
t_i=0.0166, s_i=0.0053 for Alternative B.

The equilibria computed include: (a) both countries employ taxes and subsidies, (b) unilateral action by the North or the South, and (c) both countries tax V_{21} only or subsidize V_{11} only. The results supporting Proposition 1 and 2 are presented in Table 1. The results supporting Proposition 3 appear in Table 2 (in Appendix). For brevity, we largely focus on the results that are noted as being indeterminate in Section IV, including the joint effects of a tax on V_{21} and a subsidy to V_{11}, and the effects of abatement on changes in the terms of trade.

Table 3 compares the results of both country's tax and subsidy to the Walrasian non-abatement equilibrium (as numeraire) for the small country case. After the abatement policy is imposed, the embodied pollution falls and social welfare rises in both countries (row 1 and 2). These results are independent of the factor intensity of sector X_1, (column 1 and 2 are for X_1 being V_2 intensive, Alternative A, and column 3 and 4 for X_1 being V_1 intensive, Alternative B). Contrasting these results with those in Table 1 shows that, if only V_{21} is taxed when X_1 is V_2 intensive, or if only V_{11} is subsidized when X_1 is V_1 intensive, then pollution rises and welfare falls relative to the Walrasian non-abatement equilibrium. Changes in the levels of production (row 3 and 4) depend on factor intensity. When X_1 is V_2 intensive, the supply of X_1 rises and X_2 falls, while X_1 falls and X_2 rises when X_1 is V_1 intensive. These imply that, as the optimal subsidy rate is higher (lower) than the tax rate, the subsidy effects on the levels of production dominates (is dominated by) the tax effects when X_1 is V_2 (V_1) intensive. (Recall Proposition 1 and 2, taxing V_{21} causes the supply of X_1 to fall and X_2 to rise regardless of whether X_1 is V_2 or V_1 intensive, while subsidizing V_{11} causes the supply of X_1 and X_2 to change in the opposite direction). Although welfare rises, the optimal abatement leads to a fall in GNP and a fall in the demand for X_1 and X_2 in both countries, regardless of factor intensity (row 5-7). Table 4 presents similar results for the large country case. When world prices are permitted to adjust, the price of P_{x1} falls if X_1 is V_2 intensive and rises if X_1 is V_1 intensive (row 1). These results follow from Table 3, where we observe that in the small country case, the demand falls for both goods, while the supply of X_1 rises (falls) and X_2 falls (rises) if X_1 is V_2 (V_1) intensive. As there exists an excess supply of (excess demand for) X_1 when X_1 is V_2 (V_1) intensive, the stability condition for an equilibrium requires price P_{X_1} to fall (rise). However, if only V_{21} is taxed, P_{X_1} rises, while if only V_{11} is subsidized, P_{X_1} falls, regardless of the factor intensity of X_1. The determining factor driving these results is that a tax on V_{21} causes the supply of X_1 to fall while a subsidy to V_{11} causes the supply of X_1 to rise, regardless of the factor intensity in sector X_1. (These are the results of Proposition 1 and 2).

In contrast to the small country case, the fall (rise) in P_{X_1} causes the X_1－importing country to be better (worse) off, while the X_1−exporting country to be better off in both cases, as the positive change in the utility from the abatement effects is large in the North when P_{X_1} falls (row 2). These results indicate that the welfare effects caused by the change in the terms of trade may dominate the effects caused by environmental policy, and hence, compensatory payments from the welfare gaining country to the welfare losing country may be required to encourage both countries to pursue abatement policies.

Usually, the embodied pollution always falls in the abatement country, regardless of the change in P_{X_1}. In the country not pursuing an abatement policy, pollution rises if P_{X_1} falls and X_1 is V_2 intensive.

The trade effects for the small country case are shown in Table 5. Under the small country assumption, the world market equilibrium is outside the model. If X_1 is V_2 intensive, (i.e., the North has comparative advantage in X_1), abatement in the North causes the excess supply of X_1 in the North to increase. The excess demand for X_1 in the South falls. However, if X_1 is V_1 intensive, (i.e., the South has comparative advantage in X_1), abatement in the South causes the excess supply in the South and the excess demand in the North both to fall.

The trade effects for the large country case are shown in Table 6. If X_1 is V_2 intensive, the North increases its export of X_1 when either both countries or the North alone abates pollution, while the export of X_1 falls in the North when the South abates unilaterally. These results imply that for a V_2 intensive polluting good, an abatement policy in the exporting country or in both countries cannot affect the exporting country's comparative advantage, i.e., reduce the exports of the polluting good. However, when X_1 is V_1 intensive, the South, who is then the X_1-exporting country, reduces its exports of X_1 when either both countries or the South alone introduces the policy. The North's exports increase when it abates unilaterally. These results imply that for a V_1 intensive polluting good, the abatement in the exporting country or in both countries affects the exporting country's comparative advantage, while unilateral abatement in the importing country creates a trade opportunity for the exporting country. Comparing these results with Table 4, we find that, when the world price P_{x1} falls, the X_1−exporting country (North) is better off and its exports increase if it pursues abatement, while when the world price P_{X_1} rises, the X_1−exporting country (South) is better off, but its exports fall if it pursues abatement.

VI. Conclusions

The effects of the environmental policy on social welfare and trade are analyzed in a modified general equilibrium Heckscher-Ohlin framework where pollution is produced by an input as a by-product of production, and is *embodied* in a tradable good and affects health and utility through consumption. Utility is non-homothetic to account for the demand effects of different income levels among countries. The results show that if only the polluting input is taxed, then its after tax rental rate falls if (a) this input is intensively used, and (b) world prices remain unchanged (the small country case). For this case, the effectiveness of this instrument to lower embodied pollutants is limited and may be negative depending on the extent to which the price of the polluting input falls. Instead, a tax on the polluting input in combination with a subsidy to the non-polluting input can reduce pollution and improve a country's welfare. However, for a large country or region, changes in the terms of trade may cause the importing (exporting) country to be made better off at the expense of the other if the price of polluting good falls (rises). Then, a Pareto improvement can only be reached by an optimal tax and subsidy with compensation from the country experiencing gains in its terms of trade to the other country. The optimal tax for the exporting country not only depends on its own marginal welfare loss from the effects of pollution, but also on the welfare losses that the country's exports cause on consumers in the importing country. Abatement policy applied by both countries or by one country unilaterally will not necessarily lower a country's comparative advantage in both small and large country cases, i.e., reduce its exports of polluting good.

The broader based policy implications of this analysis are that differences in pollution levels between the North and the South are to be expected and, in part, desirable due to differences in income levels and consequently differences in consumption. Neither the North nor the South should pursue policy that imposes its pollution preferences on the other. However, the country whose exports embody pollution should take into consideration an abatement policy to mitigate harmful effects on the importing country. When a country or region's abatement policy affects the terms of trade in its favor, caution must be exercised so that abatement policies are not pursued for the purpose of gaining from terms of trade effects alone. And, to repeat, changes in the terms of trade as a result of abatement may require one country to compensate the other if both are to raise their welfare levels.

Appendix

A.1 Proof of Proposition 1 and 2

A.1.1 *Background*

Following the traditional model (e.g., Woodland (1982)), given factor endowments and output prices, the unit-cost function for each sector equals the output price of this sector:

$$c_{x_1}(w_1,\ w_2) = P_{x_1}, \tag{A1}$$

$$c_{x_2}(w_2,\ w_2) = P_{x_2}.$$

The factor market clearing equations are:

$$\frac{\partial c_{x_1}}{\partial w_1} X_1^i + \frac{\partial c_{x_2}}{\partial w_1} X_2^i = \overline{V}_{1_i}, \tag{A2}$$

$$\frac{\partial c_{x_1}}{\partial w_2} X_1^i + \frac{\partial c_{x_2}}{\partial w_2} X_2^i = \overline{V}_{2_i}.$$

A.1.2 *Proof of Proposition 1 for the Signs of* $\partial w_j / \partial t$

Differentiating unit-cost functions (A1) with respect to t, holding output prices constant, yields:

$$\frac{\partial c_{x_1}}{\partial w_1}\frac{\partial w_1}{\partial t} + (1+t)\frac{\partial c_{x_1}}{\partial w_2^*}\frac{\partial w_2}{\partial t} + w_2\frac{\partial c_{x_1}}{\partial w_2^*} = 0,$$

$$\frac{\partial c_{x_2}}{\partial w_1}\frac{\partial w_1}{\partial t} + \frac{\partial c_{x_2}}{\partial w_2}\frac{\partial w_2}{\partial t} = 0,$$

where $w_2^*=(1+t)w_2$. In the matrix form, we obtain:

$$\begin{pmatrix} b_{11} & (1+t)b_{21} \\ b_{12} & b_{22} \end{pmatrix} \begin{pmatrix} \dfrac{\partial w_1}{\partial t} \\ \dfrac{\partial w_2}{\partial t} \end{pmatrix} = \begin{pmatrix} -b_{21}w_2 \\ 0 \end{pmatrix},$$

$$\frac{\partial w_1}{\partial t} = -\frac{1}{\triangle_1} b_{22} b_{21} w_2 > 0,$$

$$\frac{\partial w_2}{\partial t} = \frac{1}{\triangle_1} b_{12} b_{21} w_2 < 0, \tag{A3}$$

where b_{fj} is an input-output coefficient, for input V_f used to produce output X_j

$$\triangle_1 = b_{11}b_{22} - (1+t)b_{21}b_{12} = b_{12}b_{11}\left(\frac{b_{22}}{b_{12}} - (1+t)\frac{b_{21}}{b_{11}}\right) < 0.$$

If X_1 is V_2 intensive, i.e., $\frac{b_{21}}{b_{11}} > \frac{b_{22}}{b_{12}}$,

$$b_{1j} = \frac{\partial c_{x_j}}{\partial w_1}, \quad b_{22} = \frac{\partial c_{x_2}}{\partial w_2}, \quad b_{21} = \frac{\partial c_{x_1}}{\partial w_2^*}.$$

A.1.3. *Proof of Proposition 2 for the Signs of* $\partial w_j / \partial s$

$$\frac{\partial w_1}{\partial s} = \frac{1}{\triangle_1} b_{22} b_{21} w_1 < 0,$$
$$\frac{\partial w_2}{\partial s} = -\frac{1}{\triangle_1} b_{12} b_{21} w_1 > 0,$$

where $w_1^* = (1-s)w_1$,

$$\triangle_1 = (1-s)b_{11}b_{22} - b_{21}b_{12} = b_{12}b_{11}((1-s)\frac{b_{22}}{b_{12}} - \frac{b_{21}}{b_{11}}) < 0,$$
$$b_{11} = \frac{\partial c_{x_1}}{\partial w_1^*}.$$

A.1.4. *Proof of Proposition 1 for the Signs of* $\partial w_2^* / \partial t$

$$\frac{\partial w_2}{\partial t^*} = (1+t)\frac{\partial w_2}{\partial t} + w_2. \tag{A4}$$

Substituting (A3) into (A4) for $\partial w_2 / \partial t$ yields:

$$\begin{aligned} \frac{\partial w_2^*}{\partial t} &= \frac{1}{\triangle_1} b_{12} b_{21} w_2^* + w_2 \\ &= \frac{1}{\triangle_1}(b_{12} b_{21} w_2^* + \triangle_1 w_2) \\ &= \frac{1}{\triangle_1} b_{11} b_{22} w_2 < 0. \end{aligned} \tag{A5}$$

A.1.5 *Proof of Proposition 1 for the Signs of* $\partial X_j/\partial t$

Differentiating (A2) with respect to t, holding endowments constant, yields:

$$b_{11}\frac{\partial X_1}{\partial t}+b_{12}\frac{\partial X_2}{\partial t}+\left(\frac{\partial b_{11}}{\partial w_1}X_1+\frac{\partial b_{12}}{\partial w_1}X_2\right)\frac{\partial w_1}{\partial t}+\frac{\partial b_{11}}{\partial w_2^*}\frac{\partial w_2^*}{\partial t}X_1$$
$$+\frac{\partial b_{12}}{\partial w_2}\frac{\partial w_2}{\partial t}X_2=0,$$

$$b_{21}\frac{\partial X_1}{\partial t}+b_{22}\frac{\partial X_2}{\partial t}+\left(\frac{\partial b_{21}}{\partial w_1}X_1+\frac{\partial b_{22}}{\partial w_1}X_2\right)\frac{\partial w_1}{\partial t}+\frac{\partial b_{21}}{\partial w_2^*}\frac{\partial w_2^*}{\partial t}X_1$$
$$+\frac{\partial b_{22}}{\partial w_2}\frac{\partial w_2}{\partial t}X_2=0.$$

In the matrix form, we have

$$\begin{pmatrix} b_{11} & b_{12}\\ b_{21} & b_{22}\end{pmatrix}\begin{pmatrix}\frac{\partial X_1}{\partial t}\\ \frac{\partial X_2}{\partial t}\end{pmatrix}=-\begin{pmatrix}\left(\frac{\partial b_{11}}{\partial w_1}X_1+\frac{\partial b_{12}}{\partial w_1}X_2\right)\frac{\partial w_1}{\partial t}+\frac{\partial b_{11}}{\partial w_2^*}\frac{\partial w_2^*}{\partial t}X_1+\frac{\partial b_{12}}{\partial w_2}\frac{\partial w_2}{\partial t}X_2\\ \left(\frac{\partial b_{21}}{\partial w_1}X_1+\frac{\partial b_{22}}{\partial w_1}X_2\right)\frac{\partial w_1}{\partial t}+\frac{\partial b_{21}}{\partial w_2^*}\frac{\partial w_2}{\partial t}X_1+\frac{\partial b_{22}}{\partial w_2}\frac{\partial w_2}{\partial t}X_2\end{pmatrix}. \qquad (A\ 6)$$

Substituting (A3) and (A5) into (A6) for $\partial w_1/\partial t$ and $\partial w_2^*/\partial t$:

$$\begin{pmatrix} b_{11} & b_{12}\\ b_{21} & b_{22}\end{pmatrix}\begin{pmatrix}\frac{\partial X_1}{\partial t}\\ \frac{\partial X_2}{\partial t}\end{pmatrix}=\frac{r}{\triangle_1}\begin{pmatrix} b_{22}X_1\left(b_{21}\frac{\partial b_{11}}{\partial w_1}-b_{11}\frac{\partial b_{11}}{\partial w_2^*}\right)+b_{21}X_2\left(b_{22}\frac{\partial b_{12}}{\partial w_1}-b_{12}\frac{\partial b_{12}}{\partial w_2}\right)\\ b_{22}X\left(b_{21}\frac{\partial b_{21}}{\partial w_1}-b_{11}\frac{\partial b_{21}}{\partial w_2^*}\right)+b_{21}X_2\left(b_{22}\frac{\partial b_{22}}{\partial w_1}-b_{12}\frac{\partial b_{22}}{\partial w_2}\right)\end{pmatrix},$$

$$\begin{pmatrix}\frac{\partial X_1}{\partial t}\\ \frac{\partial X_2}{\partial t}\end{pmatrix}=\frac{w_2\,dt}{\triangle_1\triangle_2}\begin{pmatrix} b_{22} & -b_{21}\\ -b_{12} & b_{22}\end{pmatrix}\cdot$$
$$\begin{pmatrix} b_{22}X\left(b_{21}\underset{(-)}{\frac{\partial b_{11}}{\partial w_1}}-b_{11}\underset{(-)}{\frac{\partial b_{11}}{\partial w_2^*}}\right)+b_{21}Y\left(b_{22}\underset{(-)}{\frac{\partial b_{12}}{\partial w_1}}-b_{12}\underset{(-)}{\frac{\partial b_{12}}{\partial w_2}}\right)\\ b_{22}X\left(b_{21}\underset{(+)}{\frac{\partial b_{21}}{\partial w_1}}-b_{11}\underset{(+)}{\frac{\partial b_{21}}{\partial w_2^*}}\right)+b_{21}Y\left(b_{22}\underset{(+)}{\frac{\partial b_{22}}{\partial w_1}}-b_{12}\underset{(+)}{\frac{\partial b_{22}}{\partial w_2}}\right)\end{pmatrix},$$

where $\triangle_2 = b_{11}b_{22} - b_{21}b_{12} = b_{12}b_{11}\left(\frac{b_{22}}{b_{12}} - \frac{b_{21}}{b_{11}}\right) < 0.$

Thus, $\frac{\partial X_1}{\partial t} < 0$, $\frac{\partial X_2}{\partial t} > 0.$

Similarly we can prove Proposition 2 for the signs of $\partial X_j/\partial s$.

A.1.6 *Proof of Proposition 1 for the Signs of* $\partial V_{21}/\partial t$ *and* $\partial po/\partial t$:

$$\begin{aligned}\frac{\partial V_2}{\partial t} &= b_{21}\frac{\partial X_1}{\partial t} + X_1\frac{\partial b_{21}}{\partial t}\\ &= b_{21}\frac{\partial X_1}{\partial t} + X_1\frac{\partial b_{21}}{\partial w_1}\frac{\partial w_1}{\partial t} + X_1\frac{\partial b_{21}}{\partial w_2^*}\frac{\partial w_2^*}{\partial t},\end{aligned} \tag{A7}$$

where $X_1\frac{\partial b_{21}}{\partial w_1}\frac{\partial w_1}{\partial t} + X_1\frac{\partial b_{21}}{\partial w_2^*}\frac{\partial w_2^*}{\partial t}$

$$= \frac{X_1 w_2}{\triangle_1\triangle_2}\left[-b_{22}b_{21}\frac{\partial b_{21}}{\partial w_1}(b_{11}b_{22}-b_{21}b_{12}) + b_{11}b_{22}\frac{\partial b_{21}}{\partial w_2^*}(b_{11}b_{22}-b_{21}b_{12})\right].$$

Further,

$$\begin{aligned}b_{21}\frac{\partial X_1}{\partial t} = \frac{w_2}{\triangle_1\triangle_2}\Bigg\{&b_{21}b_{22}\Bigg[b_{22}X_1\left(b_{21}\frac{\partial b_{11}}{\partial w_1} - b_{12}\frac{\partial b_{11}}{\partial w_2^*}\right)\\ &+ b_{21}X_2\left(b_{22}\frac{\partial b_{12}}{\partial w_1} - b_{11}\frac{\partial b_{12}}{\partial w_2}\right)\Bigg] - b_{21}b_{12}\Bigg[b_{22}X_1\left(b_{22}\frac{\partial b_{21}}{\partial w_1} - b_{12}\frac{\partial b_{11}}{\partial w_2^*}\right)\\ &+ b_{21}X_2\left(b_{21}\frac{\partial b_{12}}{\partial w_1} - b_{11}\frac{\partial b_{12}}{\partial w_2}\right)\Bigg]\Bigg\}.\end{aligned} \tag{A8}$$

Adding (A7) with (A8) yields

$$\begin{aligned}\frac{\partial V_{21}}{\partial t} = \frac{w_2}{\triangle_1\triangle_2}\Bigg\{&b_{21}b_{22}\Bigg[b_{22}X_1\Bigg(b_{21}\underset{(-)}{\frac{\partial b_{11}}{\partial w_1}} - b_{12}\underset{(-)}{\frac{\partial b_{11}}{\partial w_2^*}}\Bigg)\\ &+ b_{21}X_2\Bigg(b_{22}\underset{(-)}{\frac{\partial b_{12}}{\partial w_1}} - b_{11}\underset{(-)}{\frac{\partial b_{12}}{\partial w_2}}\Bigg)\Bigg] - b_{12}b_{21}^2X_2\Bigg(b_{21}\underset{(+)}{\frac{\partial b_{22}}{\partial w_1}} - b_{12}\underset{(+)}{\frac{\partial b_{22}}{\partial w_2}}\Bigg)\\ &- b_{11}b_{21}b_{22}^2\underset{(-)}{\frac{\partial b_{21}}{\partial w_1}}X_1 + b_{11}^2b_{22}^2\underset{(-)}{\frac{\partial b_{21}}{\partial w_2}}X_1\Bigg\} < 0.\end{aligned}$$

As po=f(V_{21}/V_{11}), $\partial V_{21}/\partial t$<(>) 0 implies $\partial po/\partial t$ <(>) 0.

A.1.7 *Proof of Proposition 1 for the Sign of* ∂ GNP/∂ t:

We proceed by showing that the summation of the first four terms of following equation is zero:

$$\frac{\partial GNP}{\partial t} = \overline{V}_1\frac{\partial w_1}{\partial t} + \overline{V}_2\frac{\partial w_2}{\partial t} + w_2V_{21} + tV_{21}\frac{\partial w_2}{\partial t} + tw_2\frac{\partial V_{21}}{\partial t}. \qquad \text{(A9)}$$

Substituting (A3) into (A9) for $\frac{\partial w_1}{\partial w_2}$, $\frac{\partial w_2}{\partial t}$,

we obtain for the first two terms of (A9) being equal to

$$\overline{V}_1\frac{\partial w_1}{\partial t} + \overline{V}_2\frac{\partial w_2}{\partial t} = -\frac{w_2}{\triangle}(b_{22}b_{21}\overline{V}_1 - b_{12}b_{21}\overline{V}_2). \qquad \text{(A10)}$$

Substituting (A2) into (A10) for V_f, we obtain

$$\frac{w_2b_{21}}{\triangle_1}[b_{22}(b_{11}X_1 + b_{12}X_2) - b_{12}(b_{21}X_1 + b_{22}X_2)] = -w_2V_{21}\left(\frac{\triangle_2}{\triangle_1}\right).$$

Then, the summation of the first four terms of (A9) becomes:

$$\begin{aligned} &w_2V_{21}\left(1 - \frac{\triangle_2}{\triangle_1} + t\frac{1}{\triangle_1}b_{12}b_{kx}\right) \\ &\quad = \frac{1}{\triangle_1}w_2V_{21}[b_{11}b_{22} - (1+t)b_{21}b_{12} - b_{11}b_{22} + b_{12}b_{21} + tb_{12}b_{21}] \\ &\quad = 0. \end{aligned}$$

Thus, in (A9), $\frac{\partial GNP}{\partial t} = tw_2\frac{\partial V_{21}}{\partial t} < 0$, as $\frac{\partial V_{21}}{\partial t} < 0$.

Similarly, we can prove that ∂ GNP/∂ s $<$ 0.

A.2. Numerical Results

The equilibria with abatement policies are calculated for various cases: small country, large country, bilateral and unilateral abatement. The results presented here are computed relatively to the Walrasian non-abatement equilibrium as numeraire.

Table 1　Proposition 1 and 2: Numerical Results for the North, Small Country Case

	Taxing V_{21} only		Subsidizing V_{11} only	
	$V_{21}/V_{11}>V_{22}/V_{12}$	$V_{21}/V_{11}<V_{22}/V_{12}$	$V_{21}/V_{11}>V_{22}/V_{12}$	$V_{21}/V_{11}<V_{22}/V_{12}$
w_1/w_2	0.1172	-0.0082	-0.0777	0.0080
w_1^*/w_2^*	0.0376	-0.0244	-0.2154	0.0027
X_1^n	-0.0583	-0.0155	0.1287	0.0071
X_2^n	0.0568	0.0076	-0.1353	-0.0035
po^n	0.0376	-0.0244	-0.2154	0.0024
GNP_n	-0.0007	-0.00002	-0.0035	-0.000004
U_n	-0.0030	0.00007	0.0081	-0.00002

Notes: w_f: rental rate of input V_f.
$w_1^*/w_2^*=(1-s)w_1/(1+t)w_2$, where s is the subsidy rate to V_{11} and t is the tax rate on V_{21}.
X_j^n: supply of X_j in North.
po^n: embodied pollution per unit of X_1 produced in North.
$GNP_n= P_{x1}X_1^n + X_2^n$.
U_n: utility of the North.
$V_{21}/V_{11} > V_{22}/V_{12}$ implies that sector X_1 is V_2 intensive.
The similar results for the South are skipped.

Table 2　Changes in Utility, Unilateral Abatement, Small Country

		North	South
North abates pollution	$V_{21}/V_{11}>V_{22}/V_{12}$	0.007970	0.0029
	$V_{21}/V_{11}<V_{22}/V_{12}$	0.000053	0.0
South abates pollution	$V_{21}/V_{11}>V_{22}/V_{12}$	0.0	0.0068
	$V_{21}/V_{11}<V_{22}/V_{12}$	0.000019	0.000065

Note: Proposition 3 is supported by this table, i.e., the polluting good importing country benefits from the unilateral action of the exporting country.

Table 3　Regulators' Problem: Both Abate Pollution, Small Country

	$V_{21}/V_{11} > V_{22}/V_{12}$		$V_{21}/V_{11} < V_{22}/V_{12}$	
	North	South	North	South
U_i	0.0080	0.0093	0.00007	0.00007
po^i	-0.1859	-0.1859	-0.02180	-0.02180
X_1^1	0.0723	0.0557	-0.0084	-0.0083
X_2^1	-0.0766	-0.0257	0.0010	0.0093
X_{1i}	-0.0042	-0.0038	-0.00003	-0.00005
X_{2i}	-0.0009	-0.0003	-0.000002	-0.000008
GNP_i	-0.0022	-0.0013	-0.000014	-0.000024

Note: X_{ji}: demand for X_j in country i.

Table 4 Regulators' Problem: Both Abate Pollution, Large Country

	$V_{21}/V_{11} > V_{22}/V_{12}$		$V_{21}/V_{11} < V_{22}/V_{12}$	
	North	South	North	South
P_x	-0.0270		0.0036	
U_i	0.0030	0.0108	-0.0003	0.0004
po^i	-0.1401	-0.1401	-0.0147	-0.0147
X_1^1	0.0266	-0.0211	-0.00003	-0.0031
X_2^1	-0.0294	-0.0074	0.0000003	0.0035
X_{1i}	0.0082	0.0137	-0.0021	-0.0014
X_{2i}	-0.0123	-0.0058	0.0010	0.0016
GNP_i	-0.0153	-0.0090	0.0012	0.0019

Table 5 Trade Effects, Small Country

	$V_{21}/V_{11} > V_{22}/V_{12}$		$V_{21}/V_{11} < V_{22}/V_{12}$	
	Imports of X_1 in South	Exports of X_1 from North	Exports of X_1 from South	Imports of X_1 in North
North abates	-0.0207	**0.4132**	0.0	0.0315
South abates	-0.1482	0.0	**-0.0401**	-0.0002

Table 6 Trade Effects, Large Country

	$V_{21}/V_{11} > V_{22}/V_{12}$ Exports of X_1 from North	$V_{21}/V_{11} < V_{22}/V_{12}$ Exports of X_1 from South
Both abate	0.1084	-0.0098
North abates	0.1878	-0.0133
South abates	-0.0840	-0.0232

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