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TRANSBOUNDARY POLLUTION AND THE KUZNET'S CURVE IN THE GLOBAL COMMONS

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Abstract

Recent empirical work suggests an inverted U-shaped relationship between pollution and national income (the environmental Kuznet's curve). This work has typically ignored the fact that pollutants are dispersed to varying degrees. This study shows how varying levels of spatial pollution dispersion (or "publicness") can affect pollution-income relationships. A public goods model captures the idea of the "global commons" with two pollutants. The model suggests that no refutable hypotheses are possible without restrictions on income and substitution effects. With such restrictions, emission levels are lower for countries that have high pollution spillovers and larger proportions of pollution emitted within their borders. The model motivates the use of a switching regression approach to estimate the relationship between pollution emissions and national income for a set of countries. The empirical analysis incorporates two key pollution dispersion variables: transboundary pollution spillovers and the portion of pollution remaining in the country of origin. The pollution dispersion variables have a detectable effect on national pollution emissions although not necessarily those that them model predicts.

Transboundary Pollution and the Kuznet's Curve in the Global Commons

1. Introduction and Overview

This article concerns three issues. First, how do different types of pollution respond to changes in national income? Second, how does the physical dispersion or "publicness" of different types of pollution affect abatement? Third, how does this "publicness" affect the income-pollution response or environmental Kuznet's curve?

The debate over the environmental Kuznets curve (see Arrow et. al. 1995, Ezzati et. al.1998 ,Stern et. al. 1996) involves the response to local and global environmental issues as a function of income (see Runge, 1994; Farber, 1997). Recent empirical evidence suggests that nations intervene to correct environmental problems even as trade liberalization and economic growth proceed apace. Correction of environmental problems is positively correlated with income at the higher end of the national income scale, suggesting that limiting growth and trade may actually retard environmental interventions (Werner, Copeland and Taylor, 1998). Grossman and Krueger (1995), Selden and Song (1994), Lucas (1996) and others show that for many types of pollution, emissions or ambient levels of pollution at first increase with income to a peak level and then decline as income continues to increase. This is the "inverted U-shaped" or "environmental Kuznets Curve" describing the response of higher income countries to environmental externalities.

While the environmental Kuznets curve generates some optimism for proponents of economic growth (see Beckerman, 1992), some pollutants increase through the entire range of national income. For example, nitrogen oxides, carbon dioxide and CFCs seem to fit this pattern

(Selden and Song, 1993; Shafik, 1994; Holtz-Eakin and Selden, 1992), although CFC consumption and emissions have declined since the signing of the Montreal Protocol. Thus economic growth may be necessary, but not sufficient, for improvements in environmental quality.

The environmental Kuznet's curve has thus become a focus of research, controversy, and critical review in the literature (Stern et. al, 1996) and the subject of two recent editions of the journals *Ecological Economics*, and *Environment and Development Economics*. Criticism has focused on three main issues. First, the environmental Kuznet's curve (at least as it has been estimated so far) is a reduced form relationship that does not explain what leads to downturns in pollution output, especially the process of institutional reform that takes place as countries develop policies to reduce environmental pollution (Arrow et. al, 1995). This reinforces the point that reductions in environmental damage as countries increase per capita income do not happen automatically (Grossman and Krueger, 1994; Stern et. al, 1996). Second, environment impacts can feed back to lower economic performance, a factor not accounted for in virtually all studies (Arrow et. al, 1995; Ezzati et. al, 1998; Stern et. al, 1996; Rothman, 1998; de Bruyn et. al, 1998). This can be especially important in very low income countries (Barbier, 1994). Third, environmental Kuznet's curve studies have generally not accounted for the evolution of international economies and policies. The current extent of global environmental damage to the ozone layer and changes to the earth's climate regime were created in national and international economies different from those of today (Ezzati et. al, 1998). It is also unclear whether today's developing countries will be able to replicate the experience of developed countries such as the United States and Japan which reduced pollution output, in part, by importing energy intensive goods (Stern, 1996; Herendeen, 1994).

Recent work has remedied some of these problems. Panayotou (1997) incorporates institutional factors into an analysis of SO_2 concentrations by including a policy variable that accounts for respect and enforcement of contracts in a country's economy as a whole. Torras and Boyce (1998) incorporate income inequality, political rights and liberties and literacy. However, neither attempts to account for the simultaneous determination of these variables and national income – richer countries may simply have better institutions, political rights and liberties. Ezzati et. al (1998), built a simulation model with environmental feedbacks while de Bruyn (1997) performed a decomposition analysis of reductions in SO_2 emission output ratios. However, this analysis still does not explain why structural or technological changes have occurred to reduce emissions.

This paper seeks to explain observed differences in pollution income relationships different types of pollution emissions. For example, the difference between CO_2 and SO_2 emission-income relationships because people prefer to wait to reduce carbon dioxide emissions until the current scientific debate over global warming is resolved and more willing reduce SO_2 because of its immediate health effects. The cost and efficacy of pollution abatement technologies will also have an effect on where abatement efforts are concentrated (McConnell, 1997).

The central contribution of the paper, however, is to explore another possible explanation: the degree of pollution dispersion or its "publicness". Publicness in pollution occurs when local pollutants created within any one jurisdiction spill over to affect people in other jurisdictions. The more dispersed pollutants become, the more widespread are these negative spillover effects. The extra-jurisdictional impact of such pollutants makes the collective action problem of reducing them more difficult because it requires the cooperation of larger and more heterogeneous populations and multiple jurisdictions. The central idea is that people tend to place less priority on reduction of widely dispersed pollution, relative to more localized pollution, because local problems such as solid waste or bacteria in drinking water supplies are less “public” than global pollutants such as greenhouse gases or ozone depleting chemicals (see also Arrow et. al, 1995; Seldon and Song, 1994; Shafik, 1994; de Bruyn, 1997; Cole et.al, 1997; Barbier, 1997). The argument is in the tradition of Olson (1965), who noted the role of publicness in confounding collective action.

Related to the tendency to abate locally first and globally second is that as incomes rise, pollution can more easily be shifted away from immediate surroundings. Alexander (1993) captures the essence of the idea: “Their constituents, in the words of two-time director of the Environmental Protection Agency William Ruckelshaus, ‘want their garbage to be picked up but they do not want it put down, at least not in their neighborhoods.”[1] For example, household waste was (and is) often dumped close to the household in low income settings. As incomes rise garbage collection can be more readily financed, shifting what had been a problem of inner city streets to large dump sites, generally on the outskirts of cities, or into large water bodies which carry the waste away. Such wastes may also be burned, converting them into airborne pollution, or transshipped to other sites or countries. Similarly, air pollution has been shifted away from local settings by building taller smoke stacks (Wetstone and Rosencranz 1983, Selden and Song 1994, Revesz 1997).

This activity may create local public bads out of what were once private bads, and global public bads out of what were once local public bads, as localities free ride by unloading their pollution onto other jurisdicitions. The "dispersion factor" is thus a function of both the pollutant

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[1] By constituents Alexander means the people that sanitation engineers serve in dealing with solid waste problems in industrialized countries.

itself and of population density and political boundaries, none of which have been accounted for in recent analysis of the environmental Kuznet's curve.

First, a theoretical model is specified that extends earlier public goods models developed by Cornes and Sandler (1986) and Bergstrom, Blume and Varian (1987), to a model with two public bads, multiple jurisdictions and varying levels of pollution dispersion. Consumption of pollution within a jurisdiction is determined by emissions levels in each jurisdiction and by pollution dispersion coefficients defining how pollution is exchanged across jurisdictions. Comparative statics for the model suggest that with some restrictions, pollution output within a jurisdiction is lower when pollution is more localized and when pollution spillovers are high. In addition, with these restrictions there is an inverted-U shaped relationship between pollution emissions and income.

Pollution dispersion and population density also affect the income level at which the pollution emissions begin to decline. Jurisdictions with higher population densities, larger proportions of pollution remaining within their borders, and larger amounts of deposition from other jurisdictions will tend to lower their emissions per capita at lower levels of income per capita.

Second, an empirical model is presented which departs from previous empirical work by using a switching regression model rather than quadratic or cubic functions. The switching model is more flexible, allowing variables other than income to explain changes in the pollution/income relationship in a way interpretable by our theoretical model. The empirical model includes data on an – *own deposition factor*, which accounts for the portion of emissions that stay within the country of origin, as well as *spillovers of pollutants originating from other countries*. This is also a departure from previous claims that environmental Kuznet's curves exist mainly for localized pollutants (Arrow et. al, 1995; Shafik, 1994; Seldon and Song, 1994; Cole et. al, 1997; Barbier, 1997), but which do not specifically incorporate data describing the spatial dispersion of pollution. Incorporation of own deposition factor and spillovers allows us to test directly the effects of pollution dispersion on emissions levels and to compare dispersion characteristics of different pollution types. Results for sulfur dioxide and nitrogen oxide emissions, using more recent and more complete data than previous studies, support the Kuznet's relationship between emissions per capita and income per capita, but also offer a deeper explanation of why institutions may respond to the collective action problems of environmental management in differing ways.

2. Model

This section extends the public goods models of Bergstrom, Blume and Varian (1986), and Cornes and Sandler (1986) to multiple jurisdictions with multiple pollutants. The method of public goods provision (or in this case public bads abatement) is voluntary contribution. The model captures the collective action problem when pollution is dispersed in varying degrees over multiple jurisdictions. This collective action problem has two levels: within and across jurisdictions. These jurisdictions may be thought of as countries, and the transboundary spillover effects as the "global commons."

Individual agents are the only actors. Each agent is endowed with income which they may either consume or use to abate pollution. Pollution arises from consumption. Each jurisdiction produces multiple pollutants as a function of aggregate consumption and aggregate abatement. Agents can abate pollution only in their own jurisdiction, thus depending on agents in other jurisdictions to abate pollution that may spill over into theirs. Pollution types have different levels of spatial dispersion, so that spillover effects vary. Because pollution emissions are dispersed both within and across jurisdictions, agents willing to abate pollution face possible free riding from agents both within their jurisdiction and from agents in other jurisdictions.

Major comparative statics results for this model are stated in section 3 to motivate the empirical analysis. The important comparative statics results relate to jurisdictional responses of emissions, consumption levels and abatement levels to changes in income, own deposition factor, emissions spillovers originating from other jurisdictions, and population. The own deposition factor is the proportion of emissions originating from a jurisdiction that are consumed by individuals within that jurisdiction.

There are J local jurisdictions indexed by $j \in \{1,\dots,J\} = \mathbf{J}$ (nations, states, or municipalities). Each of these local jurisdictions contain I_j individuals indexed by $i_j \in \{1,\dots,I_j\} = \mathbf{I}_j$. The economy has one private good, and bads or pollutants indexed by $k \in \{1,2\}$. Private consumption of the private good is denoted by c^{i_j}. The vector $e^j \in \Re^2_+$ represents the total emissions of pollutants emanating from jurisdiction j. The vector $E^j \in \Re^2_+$ represents consumption of the two pollutants by each individual in jurisdiction j. Individuals have preferences defined over $\Re^3_+$ that are representable by a quasi-concave, twice continuously differentiable utility function $u^{i_j}: \Re^3_+ \to \Re$. The utility function $u^{i_j}\left(c^{i_j}, E^j\right)$ does not depend on e^j directly, is strictly increasing in c^{i_j}, and strictly decreasing in the i_jth individual's pollution consumption E^j.

Each individual i_j is endowed with a quantity $\omega^{i_j} \in \Re_+$ of the private good, which we will think of as income. The aggregate endowment of jurisdiction j is then $\omega^j = \sum_{i \in \mathbf{I}_j} \omega^{i_j}$.

Individuals allocate their endowment to consumption c^{i_j} and to abatement of the *two* public pollutants or bads $q_k^{i_j}$, k = 1,2. Consumption and contributions to abatement must satisfy the constraint $c^{i_j} + q_1^{i_j} + q_2^{i_j} \leq \omega^{i_j}$. The *two* pollutants are produced as a by-product of consumption but may be reduced by abatement. These relationships are defined by:

$$e_k^j \geq h_k\left(C^j, Q_k^j, \omega^j\right) \quad k=1,2 \tag{1}$$

where $C^j = \sum_{i_j \in \mathbf{I}_j} c^{i_j}$, $Q^j = \sum_{i_j \in \mathbf{I}_j} q^{i_j}$, and the functions $h_k : \Re_+^2 \to \Re$ are continuous, increasing in C^j and decreasing in Q_k^j. The income parameter in (1) captures the idea of different technologies for different levels of income. For example, higher income countries may employ more efficient technologies, which produce less pollution for a given level of consumption. We shall assume that h_k is twice continuously differentiable in consumption, abatement and in the income parameter. Hence, pollution of both types originating from jurisdiction j is increased when consumption of commodities by residents of jurisdiction j increases. Pollution of type *k* may be decreased by directing resources Q_k^j to its abatement. Hence, effort to reduce pollution of a particular type may take the form of direct physical reductions in pollution through abatement or by reducing consumption. The set of feasible emissions and consumption possibilities are defined by:

$$\begin{aligned} Y^j\left(E^{-j}, \omega^j, \alpha^j\right) = \Big\{ & \left(C^j, E^j, e^j\right) \in \Re_+^5 \Big| \exists\ Q_1^j \geq 0, Q_2^j \geq 0 \text{ s.t.} \\ & C^j + Q_1^j + Q_2^j \leq \omega^j,\ e_k^j = h_k\left(C^j, Q_k^j; \omega^j\right), E_k^j = \alpha_k^j e_k^j + E_k^{-j} \ , k = 1,2 \Big\} \end{aligned} \tag{2}$$

and the consumption C^j frontier of this set is represented by the function $f^c\left(e_1^j, e_2^j, \omega^j\right)$ which represents the maximum consumption that can be obtained given $\left(e_1^j, e_2^j\right)$ and ω^j (see Figure 1).

Pollution emissions e^j are distinguished from pollution consumption E^j, because pollution emitted in any one jurisdiction *j* may spill over into other jurisdictions. For all individuals $i_j \in \mathbf{I}_j$, consumption of pollutants is given by:

$$E_k^j = \alpha_k^{j1} e_k^1 + \alpha_k^{j2} e_k^2 + \ldots + \alpha_k^{jJ} e_k^J \qquad (3)$$

where $\alpha_k^{jm} \in [0,1]$, $j, m \in \mathbf{J}$, and k=1,2 describes how much of a unit vector of pollution type k emitted in jurisdiction m is consumed by individuals in jurisdiction j. The amount of pollution of type *k* originating from spill-ins from outside jurisdictions is given by $E_k^{-j} = E_k^j - \alpha_k^{jj} e_k^j$. While this framework allows a large number of situations to be modeled, in terms of non-excludability and rivalness (see Sandler and Sargent 1995), we shall restrict the discussion to the case: $0 < \sum_{m \in \mathbf{J}} \alpha_k^{jm} \leq 1$, and $\alpha_k^{jm} > 0$ for all $m, j \in \mathbf{J}$ which implies that pollution type k is "rival" across jurisdictions and that pollution type k is non-excludable across all individuals and jurisdictions.

A Nash equilibrium for this economy is then defined as a list of allocations $\left(\bar{c}^{i_j}, \bar{q}_1^{i_j}, \bar{q}_2^{i_j}, \bar{E}_1^j, \bar{E}_2^j\right)_{\forall i_j \in \mathbf{I}_j, j \in \mathbf{J}}$ such that for each i_j and each j (i) $\bar{c}^{i_j}, \bar{q}_1^{i_j}, \bar{q}_2^{i_j}, \bar{E}_1^j, \bar{E}_2^j$ solve:

$$\max_{c^{i_j}, q_1^{i_j}, q_2^{i_j}, E_1^j, E_2^j} u^{i_j}\left(c^{i_j}, E_1^j, E_2^j\right) \qquad (4)$$

$$\text{s.t. } \left(c^{i_j} + q_1^{i_j} + q_2^{i_j}\right) \leq \omega^{i_j} \qquad (5)$$

$$E_k^j \geq \alpha_k^{jj} h_k\left(c^{i_j} + \overline{c}^{-i_j}, q_k^{i_j} + \overline{q}_k^{-i_j}, \omega^j\right) + \sum_{\substack{m\in\mathbf{J}\\ m\neq j}} \alpha_k^{jm} h_k\left(\overline{C}^m, \overline{Q}_k^m, \omega^j\right) \tag{6}$$

$$h_k\left(C^j, Q_k^j\right) \geq 0 \qquad \forall k \in \mathbf{K} \tag{7}$$

all $i_j \in \mathbf{I}_j$ and $j \in \mathbf{J}$ where $\overline{c}^{-i_j} = \sum_{\ell_j \in \mathbf{I}_j, \ell_j \neq i_j} c^{\ell_j}$ and $\overline{q}_k^{-i_j} = \sum_{\ell_j \in \mathbf{I}_j, \ell_j \neq i_j} \overline{q}_k^{m_j}$ for all $k = 1,2$. When $q_k^{i_j} > 0$ then agent i_j is a contributor to the abatement of pollution type k. If the equilibrium is an interior solution (i.e., $q_k^{i_j} > 0$ for k=1,2), the equilibrium first order conditions for this Nash equilibrium may be manipulated to obtain a tangency relationship between a given agent i_j's indifference curves and marginal rates of transformation between consumption and pollution:

$$-\frac{u_{E_k}^{i_j}}{u_c^{i_j}} = \frac{1}{\alpha_k^{jj}\left(h_{kC^j} - h_{kQ^j} + h_{kQ^j}\dfrac{h_{\ell C^j}}{h_{\ell Q^j}}\right)} = \frac{1}{\alpha_k^{jj}}\frac{\partial f^c}{\partial e_k^j}, \quad k = 1,2; \ell \neq k \tag{8}$$

where $u_{E_k}^{i_j}$ and $u_c^{i_j}$ are marginal utility of emissions and consumption respectively and h_{kC^j} and h_{kQ^j} are marginal changes in emissions of type k with respect to consumption and abatement activity. The left hand side of this equation is the marginal rate of substitution between pollution type k and consumption of the private commodity. The right hand side is the marginal rate of transformation between consumption of the private commodity and pollution type k, $\left(\partial f^c / \partial e_k^j\right)$, adjusted by the fraction of pollution that individual i_j receives from emissions generated in his own jurisdiction, α_k^{jj}. The equality achieved at this tangency point is the familiar condition, for a given jurisdiction that MRS=MRT.

3. Comparative Statics Results

The theoretical results presented in this section show that when pollution stays close to the point of origin, abatement effort will tend to be greater and hence pollution emissions lower than when pollution is dispersed more widely. When pollution spillovers are increased pollution abatement is also increased. Substitution effects, or changes in the willingness to substitute one pollutant for another, or substitute pollution for consumption, may undo both of these results. Hence, the need for the empirical analysis which follows.

The first result concerns how pollution changes when income changes, which is the underlying Kuznet's relationship. For this result and all that follow, we assume that individual utility functions u^{i_j} are strictly quasi-concave twice continuously differentiable and identical for each individual within a jurisdiction ($u^{i_j} = u^j$). We will also assume that each individual within a jurisdiction *j* has identical income or $\omega^{i_j} = \omega^j$. Finally, we will assume that increases in either pollutant will increase the rate at which individuals are willing to trade off consumption for decreases in pollution. This means that consumer utility functions satisfy $\partial\left(-u_{E_k}/u_c\right)\big/\partial E_k > 0$ for $k = 1,2$.

Proposition 1. *Assume that pollution reduction is a normal good* ($\partial\left(-u_{E_k}/u_c\right)\big/\partial c > 0$ *for* $k = 1,2$) *and the marginal rate of transformation between consumption and emissions decreases with increases in income* $\left(f^c_{e_k\omega} \le 0\right)$ *for all* (e_1, e_2, ω) *and individuals within jurisdiction* j *. Then i) if all members of jurisdiction j are contributors to reduction of both types of pollution emissions* ($k = 1,2$), $\frac{\partial e_1^j}{\partial \omega^j} < 0$ *or* $\frac{\partial e_2^j}{\partial \omega^j} < 0$ *and; ii) if no members of jurisdiction j are contributors to reduction of pollution then* $\frac{\partial e_k^j}{\partial \omega^j} > 0$ *for* $k = 1,2$. ***Proof:*** *See Appendix A.*

If pollution is a normal good, the more of the private good consumers have and/or the more pollution there is the more they want to reduce pollution. Under these conditions we would expect that when income increases beyond some critical point individuals within jurisdictions would want to decrease the level of pollution. While Proposition 1ii) suggests that at very low incomes no effort is expended on abatement and that increases in income will lead to increases in emissions, the effect of an increase in income at higher incomes where jurisdictions may be actively abating is more ambiguous. Emission changes are complicated by the magnitude of changes in marginal rates of substitution between the two pollutants and the marginal rate of transformation between consumption and income $\left(f^{c}_{e_k\omega}\right)$. For example, we might hypothesize that emissions of pollution of type A will decrease when spillovers of pollution of type A originating from other jurisdictions increase. However, when their is more than one pollutant, the increase in pollution type A may lead individuals to become more concerned about other pollutants, possibly because of some interaction effect, leading individuals to decrease emissions of the other pollutants instead of type A.

A crucial assumption in proposition 1 is that the marginal rate of transformation between consumption and emissions decreases with an increase in income $\left(f^{c}_{e_k\omega} \leq 0\right)$, which means that as income increases the jurisdiction is more capable of reducing pollution given a unit reduction in consumption. If this assumption is true then emissions will decrease for at least one of the pollutants, otherwise we could not say whether emissions increase or decrease with income. One interpretation is that richer countries use more efficient technologies. However, even with this assumption the result implies that the normal good assumption for the environment is not sufficient to generate a downward sloping relationship between income and pollution for all emission types. As income levels and pollution levels change, priorities for abatement may change, resulting in increases in some type(s) of pollution. However, the normal good assumption is sufficient, along with the technological assumption, to ensure that pollution will decrease for at least one pollutant.

Proposition 2. *If all members of a jurisdiction contribute to reduction of both types emissions* ($k = 1,2$), *then emissions for at least one type decrease when emissions spillovers or own deposition factor increases. That is* $\partial e_1^j \big/ \partial \rho^j < 0$ *or* $\partial e_2^j \big/ \partial \rho^j < 0$ *for any parameter* $\rho^j \in \left\{ E_1^{-j}, E_2^{-j}, \alpha_1^j, \alpha_2^j \right\}$. ***Proof:*** *See Appendix A.*

When individuals within jurisdictions contribute to abatement of both types of pollution, an increase in the portion of pollution consumed in the jurisdiction of origin (α_1^{jj} or α_2^{jj}) or in pollution spillovers (E_1^{-j} or E_2^{-j}) will increase abatement of either pollution type. Another interpretation is that if there are two otherwise identical jurisdictions that differ in own deposition factor or emissions spillovers then emissions will be lower for at least one type of pollution in the jurisdiction with the larger own deposition factor or transboundary spillovers. It is possible for the cross effects to be negative ($\partial e_2^j \big/ \partial \alpha_1^{jj} < 0$ or $\partial e_2^j \big/ E_1^{-j} < 0$) and not the direct effects, because substitution and/or income effects, which reflect a strong tendency to change abatement priorities, may over-ride the direct effects.

Proposition 3 *Suppose the utility functions are additively separable. Then* $\dfrac{\partial e_k^j}{\partial \alpha_k^j} < 0$ *and* $\dfrac{\partial e_k^j}{\partial E_k^{-j}} < 0$, $k = 1,2$. ***Proof:*** *See Appendix A.*

Separability removes the substitution effects from the utility function. Without substitution effects, increased spillovers and pollution consumption leads to a decrease in emissions. Conversely, decreased spillovers from other jurisdictions lead to a decrease in emissions. This is the expected free riding effect as individuals is to increase their own emissions when others decrease them.

Propositions 1-3 show that with multiple pollutants, emissions change with change in income, spillovers, and own deposition factor. If substitution and income effects are sufficiently large then jurisdictional responses to changes these important variables may not conform to our intuition. However, if substitution and income effects are small then the restrictions in proposition 3 are sufficient to show that emissions, consumption and abatement change in the expected direction.

Another issue is what happens to emissions when population increases. On the one hand, emissions will increase when an additional individual is added to the population. However, if pollution reduction is a normal good then the willingness to trade off consumption for decreases in pollution will increase. While the end result is ambiguous under the most general assumptions, if substitution effects and income effects are removed from the utility function and the technology is linear, then jurisdictions with higher population, everything else equal, will have higher pollution emissions, even in a country that is actively abating pollution However, per capita consumption decreases under these assumptions, which means that total per capita resources allocated to abatement of both pollutants increases. Hence emissions per capita will decrease for at least one pollutant.

Proposition 4. *Population Comparative Statics. Assume that the utility functions are additively separable, pollution reduction is a normal good, and that the emissions/consumption technologies are linear or* $e_k^j = \beta_k C^j - \theta_k Q_k^j$ *for* k=1,2. *Let* $\tilde{e}_k^j$, $\tilde{C}^j$, $\tilde{Q}_k^j$ *represent jurisdictional responses under* $\tilde{I}^j$ *and* e_k^j, C^j, *and* Q_k^j *represent equilibrium allocations under* I^j. *Assume all other parameters, utility functions, and technologies are the same. Let all individuals be contributors to abatement for per-capita income level* ω^j. *If* $\tilde{I}^j > I^j$ *then* $\tilde{e}_k^j > e_k^j$, $\tilde{C}^j > C^j$ *and*

$\tilde{Q}_1^j + \tilde{Q}_2^j > Q_1^j + Q_2^j$. In addition, $\tilde{C}^j/\tilde{I}^j < C^j/I^j$, $\left(\tilde{Q}_1^j + \tilde{Q}_2^j\right)/\tilde{I}^j >$ $\left(Q_1^j + Q_2^j\right)/I^j$ and $\tilde{e}_k^j/\tilde{I}^j < e_k^j/I^j$ for k=1 or 2. ***Proof:*** *See Appendix A.*

Own deposition factor, spillovers and population levels may also effect the critical level of ω^j, where the emissions-income relationship turns from positive to negative. Again, the effects of these factors are ambiguous unless strict assumptions are imposed. However, when the utility function is additively separable and the emissions technology is linear, increased spillovers, own deposition factors and higher populations should decrease this critical level.

Proposition 5. *Assume that the utility functions are additively separable, pollution reduction is a normal good, and that the emissions/consumption technologies are linear or $e_k^j = \beta_k C^j - \theta_k Q_k^j$ for k=1,2. Suppose that $\hat{\alpha}_1^{jj} > \overline{\alpha}_1^{jj}$, $\hat{E}_1^{-j} > \overline{E}_1^{-j}$ and $\hat{I}^j > \bar{I}^j$. Let $\overline{\omega}^j$ be the critical income associated with $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ such that when $\omega^j < \overline{\omega}^j$, e_1^j is increasing in ω^j and when $\omega^j \geq \overline{\omega}^j$ e_1^j is decreasing in ω^j. Let $\hat{\omega}^j$ be the critical income level for $\left(\hat{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$, $\left(\overline{\alpha}_1^{jj}, \hat{E}_1^{-j}, \bar{I}^j\right)$ or $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \hat{I}^j\right)$. Assume that $\overline{Q}_2^j = 0$. Then in each case $\hat{\omega}^j < \overline{\omega}^j$.* Proof: See Appendix A

Proposition 5 suggests that the income level at which emissions are reduced, is likely to be affected by many factors. This might indicate that empirical analysis could be improved by incorporating variables that shift the critical income level.

The results presented in this section show that when pollution stays close to the point of origin, abatement effort will tend to be greater and hence pollution emissions lower than when pollution is dispersed more widely. When pollution spillovers are increased pollution abatement is also increased. Substitution effects, or changes in the willingness to substitute one pollutant for another, or substitute pollution for consumption may undo these results. Hence, the need for the empirical analysis which follows.

4. Empirical Model

This section investigates two pollution-income relationships: sulfur dioxide and nitrogen oxides. Nitrogen oxides tend to be more dispersed than sulfur dioxides. The first objective is to estimate an empirical relationship between pollutant emissions and income using a switching regression model to test the theory and to compare it with previous empirical results. The second objective is to extend the empirical model to include the spatial aspects of transboundary pollution spillovers and the fraction of pollution (own deposition factor) remaining in the country of origin[2]. Results are then compared to the comparative statics above. Sulfur dioxide and nitrogen oxides were chosen because they offer the largest possible emissions databases and because they are the only two pollutants for which transbounary data is available. The transboundary movement of these pollutants is also uneven due to wind, degree of mixing with higher atmospheric layers and rainfall, creating enough variation in deposition rates and own deposition to test our theory. Previous analysis of pollution - income interactions has relied mainly on quadratic or cubic equations (Grossman and Krueger 1995; Selden and Song, 1994; and Shafik 1994, Cole et. al. 1997, Panayotou 1997). The analysis here is instead a deterministic switching regression approach suggested by Goldfeld and Quant (1971). The switching approach is useful because it is reminiscent of the theoretical model presented in the previous section. Two regimes, representing a "high" and the other a "low" level of pollution abatement, are posited:

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[2] This aspect of our analysis, is similar to that of Murdoch, Sandler and Sargent (1997) who estimate models of voluntary cutbacks of SO_2 and NO_x in Europe. However, our data is composed of a panel set of data, while Murdoch, Sandler, and Sargent (1997) use data reflecting change in emissions over a period of time.

$$\begin{aligned}\frac{e_k^{jt}}{I^{jt}} &= \beta_{k0} + \beta_{k1}\omega^{jt} + \beta_{k2}\frac{I^{jt}}{A^j} + \beta_{k3}X_0^{jt} + u_{k1}^{jt} & jt \in \text{regime}\,1 \\ \frac{e_k^{jt}}{I^{jt}} &= \beta_{k5} + \beta_{k6}\omega^{jt} + \beta_{k7}\frac{I^{jt}}{A^j} + \beta_{k8}\alpha_k^{jjt} + \beta_{k9}\left(\frac{\alpha_k^{jt}e_k^{-jt}}{A^j}\right) + \beta_{k10}X_0^{jt} + u_{k2}^{jt}, & jt \in \text{regime}\,2\end{aligned} \tag{10}$$

where e_k^{jt} is nation j's emissions of sulfur dioxides ($k = s$) or nitrogen oxides ($k = n$), ω^{jt} is GDP per capita, I^{jt} is population, α^{jjt} is country j's own deposition, α_k^{jt} is a vector of emissions transport coefficients, and e_k^{-jt} is a vector of "other country" emissions, t is the time period, X_0^{jt} is a vector of other covariates common to both regimes, and u_{k1}^{jt} and u_{k2}^{jt} are error terms for regime 1 and 2 respectively. Note that here pollution spillovers for country *j* are $E^{-jt} = \alpha_k^{jt}e_k^{-jt}$, which we divide by A^j to provide a proxy for dispersion of pollution spillovers within country *j*. The model is reminiscent of the public bads model in the previous section in the sense that regime 1 represents the corner solution where no resources are expended to control pollution. Regime 2 can be thought of as the case where contributions are made to abate the pollutants.

The statistical model is a random effects model with error terms composed of two components:

$$u_{k1}^{jt} = \gamma_{k1}^{j} + \varepsilon_{k1}^{jt}$$

$$u_{k2}^{jt} = \gamma_{k2}^{j} + \varepsilon_{k2}^{jt}.$$

The error components γ_{k1}^{j} and γ_{k2}^{j} account for differences in individual country behavior, but which can vary across the two regimes. The error components ε_{k1}^{jt} and ε_{k2}^{jt} are within country errors that may also have different variances across the two regimes.

The model orders the data according to income, splitting it at some low level of ω^{jt}. Parameter estimates are then estimated for the two sets of data. The database is then split again at the next highest level of income and the parameters are estimated again. This is done until the highest level of income is reached. The switching point is the level of income ω^* that yields the highest value for the joint likelihood function (i.e. the sum of the likelihoods for the two equations estimated for each division of the database). This is the procedure suggested in Judge et. al. (1985) and used by Stratmann (1992) in an empirical study.

Comparative statics suggest that the portion of emissions remaining in the country of origin, the level of spillovers or other factors might influence when to begin abatement. Because splitting the database raises combinatorial problems, we employ the method of Goldfeld and Quandt (1973) using maximum likelihood techniques, and define a step function $g\left(\theta_k x_k^{jt}\right)$ where $g\left(\theta_k x_k^{jt}\right) = 1$ when $\theta_k x_k^{jt} > 0$ and $g\left(\theta_k x_k^{jt}\right) = 0$ when $\theta_k x_k^{jt} \leq 0$. Thus x_k^{jt} will include a constant 1, income per capita ω^{jt}, population density, own deposition factor, pollution spillovers originating from other countries, and other covariates. The symbol θ_k is an unknown parameter vector, including a constant. Equation (10) can then be written as one equation.[3]

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[3] The equation is written somewhat differently here than in (10), because β_{ko}, β_{k1}, β_{k2} and β_{k4} are chosen for both regimes in (11). The coefficients β_{k5} to β_{k7} and β_{k10} in (10) can be recovered from (11) as follows, $\beta_{k5} = \beta_{ko} + \tilde{\beta}_{k5}$, $\beta_{k6} = \beta_{k1} + \tilde{\beta}_{k6}$, $\beta_{k7} = \beta_{k2} + \tilde{\beta}_{k7}$, and $\beta_{k10} = \beta_{k3} + \tilde{\beta}_{k10}$. Note, that the error term u_k^{jt} accounts for heteroskedasticity across the two regimes. To avoid the combinatorial problem the function g must be continuous and have a range between 0 and 1. Goldfeld and Quant (1973) suggest that any S-shaped function that is close to 0 when $\theta_k x_k^{jt}$ is very negative and close to 1 when $\theta_k x_k^{jt}$ is very positive should work well - such as the cumulative normal distribution or logistic functions. The empirical analysis presented in this chapter was done with the logistic function:

$$g\left(\theta_k x_k^{jt}\right) = \frac{1}{1 + e^{-\theta_k x_k^{jt}}} \qquad (12)$$

With this approach the level of differentiation between regimes can be strong or weak, depending on magnitude of the parameters in θ_k.

$$\frac{e_k^{jt}}{I^{jt}} = \beta_{ko} + \beta_{k1}\omega^{jt} + \beta_{k2}\frac{I^{jt}}{A^j} + \beta_{k3}X_0^{jt} + \beta_{k4}X_1^{jt}$$

$$g\left(\theta_k y_k^{jt}\right)\left(\tilde{\beta}_{k5} + \tilde{\beta}_{k6}\omega^{jt} + \tilde{\beta}_{k7}\frac{I^{jt}}{A^j} + \beta_{k8}\alpha_k^{jjt} + \beta_{k9}\left(\frac{\alpha_k^{jt}e_k^{-jt}}{A^j}\right) + \tilde{\beta}_{k10}X_0^{jt} + \beta_{k11}X_2^{jt}\right) + u_k^{jt} \tag{11}$$

To identify a specific parameter that may be interpreted as the degree of differentiation between regimes consider the constant term (θ_{1k}) in the switching equation

$$\theta_k x_k^{jt} = -\theta_{1k} + \theta_{2k}\omega^{jt} + \theta_{3k}\frac{I^{jt}}{A^j} + \theta_{4k}\alpha_k^{jjt} + \theta_{5k}\left(\frac{\alpha_k^{jt}e_k^{-jt}}{A^j}\right).$$

Let $-\theta_k = \rho(-100)$ and $\theta_{nk} = \rho\tilde{\theta}_{nk}$ for n=1,…,6. Then

$$\theta_k x_k^{jt} = \rho\left(-100 + \tilde{\theta}_{2k}\omega^{jt} + \tilde{\theta}_{3k}\frac{I^{jt}}{A^j} + \tilde{\theta}_{4k}\alpha_k^{jjt} + \tilde{\theta}_{5k}\left(\frac{\alpha_k^{jt}e_k^{-jt}}{A^j}\right) + \tilde{\theta}_{6k}X_s^{jt}\right), \tag{13}$$

where ρ can be interpreted as the degree of discrimination between regime 1 and 2. The degree of discrimination reflects uncertainty in our ability to distinguish whether a data point belongs to regime one or two. Another way of interpreting the model is to assume that there is a "continuous mixture of regimes". The parameter ρ can also be interpreted as the "fuzziness" exhibited by nature in generating the data (Goldfeld and Quandt 1972). Estimates of our model for sulfur dioxide and nitrogen oxides were also carried out jointly, with contemporaneous correlation between random effects and errors to increase the efficiency of the estimation of the parameters[4].

[4] To account for differences in variances of error terms in the two regimes, the term u_k^{jt} can be written:

$$u_k^{jt} = \gamma_k^j + \left(1 - g\left(\theta_k x_k^{jt}\right)\right)u_{k1}^{jt} + g\left(\theta_k x_k^{jt}\right)u_{k2}^{jt}$$

The data is a panel set which includes observations for 48 countries for years1970, 1975, and 1980 to 1993 for a total of 733 observations (see Appendix on data sources).

5. Empirical Results

In this section we present results for two jointly estimated sulfur dioxide and nitrogen oxide models, reported in tables 1 and 2 respectively. Both models include GDP/capita, and population density variables, pollution dispersion variables, and regional dummy variables. The purpose of the empirical analysis is to determine whether: i) pollution dispersion variables affect pollution-GDP relationships, ii) our data supports the restricted theoretical model comparative statics results , and (iii) whether the more widely dispersed pollutant (in this case NO_x) switches to a more interventionist regime 2 at a higher level of income. We take nitrogen oxides to be the more widely dispersed pollution because each country, its own deposition factor for NO_x is less than that for SO_2. The average difference between deposition factors for SO_2 and NO_x is 6.12%. Model 2 adds a restriction to the model that requires the switching points for sulfur dioxide be greater than or equal to that of nitrogen oxides. This provides a test for the hypothesis that the

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We also recognize that there may be differences in the variance of γ_k^j across the two regimes. However, the some countries will have some observations in regime 1 and other observations in regime 2. Hence, we will let γ_{k1}^j be the within country error component for pure regime 1 countries and γ_{k2}^j be the within country error component for pure regime 2 countries. For countries with observations in both regimes γ_k^j is defined:

$$\gamma_k^j = \frac{1}{T^j}\sum_{t=1}^{T^j}\left(\left(1-g\left(\theta_k x_k^{jt}\right)\right)\gamma_{k1}^j + g\left(\theta_k x_k^{jt}\right)\gamma_{k2}^j\right)$$

switch point for the more widely dispersed pollution, nitrogen oxides, occurs at a higher level of income.

The switching parameters for both the sulfur and nitrogen models are highly significant. However, the signs of the parameters for own deposition factor, the spill-over variable, and population density do not correspond to that predicted by the restricted theoretical model described in section 3 (i.e., the model that restricts substitution and income effects). The GDP per capita variable is positive indicating that countries with larger GDP/capita are more likely to be in regime 2. The negative coefficients for population density, own deposition factor and the spill-over variable indicates that the larger these variables are, the more likely the country is identified as a regime 1 country. The result for own deposition factor may be driven partially by the United States and Canada, which have large own deposition factors and whose emissions are high relative to other developed countries.

In the nitrogen models the switching parameters for income is significant and of the expected sign. Unlike the sulfur model, the coefficients on own deposition factor are of the expected sign and significant. The regime 1 to regime 2 switch points for sulfur dioxide and nitrogen oxide, when all other variables are held at their means, are $11,089 and $12,010 respectively[5]. Ninety-five percent confidence intervals for these switch points are [$10,827, $11,351] for sulfur and [$11,748, $12,272] for nitrogen. Inclusion of the constraint requiring the sulfur dioxide switch point be greater than or equal to that of nitrogen oxides indicates that there is a significant difference between these two income levels (see chi-square test in table 1).

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which is a weighted average of the regime 1 and 2 errors with the weights defined as the switching function values for each observation within the country. Hence, in estimating our model the variance-covariance matrix accounts for within and between country error components and heteroskedasticity across both components.

[5] Switch points are defined where equation 12 equals 0.5 and equation 13 equals 0.

This result corresponds to what we would expect for more widely dispersed pollutants – abatement should begin at higher incomes.

The parameter estimates for regime 1 income variables are positive and significant at the p-value level of 0.01. Population density estimates are not significantly different from zero for both pollutants. The regime 2 parameter for the constant term is positive for both pollutants as expected. For the GDP per capita variable, the parameter estimates are significantly negative for both sulfur and nitrogen dioxide. For sulfur dioxide, the sum of this parameter (-1.1286) and the regime 1 parameter (0.7399) is negative (-0.3887) and significantly different from zero at the p-level of 0.01. For nitrogen, the sum of these two variables is positive (0.0685) and significantly different from zero at the p-value of .05. However, the slope is significantly lower than the regime 1 slope. The positive slope for nitrogen oxides also supports the notion that widely dispersed pollutants receive less abatement attention than less dispersed or more local pollutants. However, it may also indicate higher costs and lower preferences for abatement.

The sign of the population density parameter for regime 2 is positive for the sulfur dioxide model and negative for the nitrogen oxide model. Hence, increased population density tends to be associated with higher sulfur dioxide emissions per capita and lower nitrogen oxide emissions per capita. The restricted model predicts lower emissions per capita. Hence, for population density, only the nitrogen results conform to the restricted theoretical model.

The regime two coefficients for own deposition factor and spillovers are negative and significantly different from zero in both models. Hence, countries whose emissions tend to be retained within their borders tend to have lower emissions. In addition, countries with larger transboundary spillovers tend to have lower emissions. This conforms to what the restricted theoretical model predicts. These estimates are not just statistically significant but are also significant in terms of effect sizes expressed in terms of elasticities. Elasticity estimates for own deposition factor are –0.85 for sulfur dioxide and –0.49 for nitrogen oxides (see Table 3). This means that countries with own deposition factors 1% higher will have lower emissions by factors of –0.84% and –0.49% respectively. For spillovers, the elasticity estimates are smaller but still significant at –0.19 and –0.17 for sulfur and nitrogen respectively.

Elasticity estimates are less convincing for population density with absolute values of estimates less than 0.05 even for statistically significant parameters, in all cases except for nitrogen oxides in regime 2. However, the elasticity estimate for population density in regime two was still rather low in absolute value at –0.09. Elasticity estimates for switching point shifts are also quite low, even for statistically significant parameters. Only the estimates for own deposition factors were greater in magnitude than 0.1. Hence, population density and spillovers, although they may be significant in a statistical sense, do not seem to significantly affect switches to a pollution abatement regime in a practical sense.

The coefficient for the time trend was negative and significant in the case of sulfur dioxide and positive but not significant for nitrogen oxide. This indicates that the trend for sulfur dioxide emissions per capita is decreasing over time. The dummy variables for Eastern Europe are large, positive and significant for both nitrogen and sulfur dioxide – as we would expect for the former Soviet Bloc countries. The dummy variable for North America is also large. This is probably reflective of the large metal smelting industries in both of these countries.

Table 1. Switching model results for emissions per capita as dependent variable. Parameter estimates are for sulfur dioxide.

		Model 1	Model 2
Switching Parameters	Discrimination Parameter	.5242*** (0.1378)	0.4328*** (0.0912)
	GDP/Capita	10.8978*** (0.4774)	10.1651*** (0.3415)
	Pop. Density	-0.0425*** (0.0107)	-0.0326*** (0.0097)
	Own Dep. SO_2	-0.8369*** (0.1349)	-0.6343*** (0.1014)
	SO_2 Spillovers	-.154*** (0.0572)	-0.0677 (0.0421)
Common Parameters	Year	-0.1139*** (0.0129)	-0.1133*** (0.0129)
	North America	12.3365*** (1.9156)	12.2970*** (1.8807)
	Europe	-0.6632 (1.1152)	-0.6283 (1.1022)
	Eastern Europe	11.7639*** (1.4993)	11.8097*** (1.5004)
Regime One Parameters	Constant	1.1367 (0.8019)	1.1724 (0.8395)
	GDP/Capita	0.7399*** (0.0839)	0.7196*** (0.0828)
	Pop. Density	-.0036 (0.0044)	-0.0032 (0.0044)
Regime Two Parameters	Constant	14.2464*** (1.2399)	14.0731*** (1.2830)
	GDP/Capita	-1.1286*** (0.0912)	-1.0971*** (0.0953)
	Pop. Density	0.0052*** (0.0016)	0.0054*** (0.0016)
	Own Dep. SO_2	-0.1902*** (0.0309)	-0.1907*** (0.0306)
	SO_2 Spillovers	-0.0424*** (0.012)	-0.0469*** (0.0118)
	Log Likelihood	878.02	872.56
	χ^2	10.907***	
	(d.f.)	1	
	Comparison	Model 2	

*Indicates the parameter is significant at a p-value of 0.1. ** Significant at a p-value of 0.05.
*** Significant at a p-value of 0.01. All single parameter tests are two-tailed.
Models 1 and 2 were estimated jointly with the nitrogen oxide model with contemporaneous correlation between random effects and errors.

Table 2. Switching model results for emissions per capita as dependent variable. Parameter estimates are for nitrogen oxides

		Model 1	Model 2
Switching Parameters	Discrimination Parameter	.5242*** (0.1380)	0.4328*** (0.0912)
	GDP/Capita	7.6390*** (0.1168)	7.3908*** (0.0191)
	Pop. Density	-0.0689*** (0.0056)	-0.0642*** (0.0058)
	Own Dep. NO_x	0.7717*** (0.1293)	1.3800*** (0.0832)
	NO_x Spillovers	0.0245 (0.0777)	0.0054*** (0.0000)
Common Parameters	Year	0.004 (0.0043)	0.0039 (0.0043)
	North America	8.7252*** (1.3064)	8.4006*** (1.1909)
	Europe	0.9432** (0.4039)	0.9287*** (0.4000)
	Eastern Europe	1.9252*** (0.4339)	1.8940*** (0.4435)
Regime One Parameters	Constant	0.0847 (0.2344)	0.0924 (0.2364)
	GDP/Capita	0.2549*** (0.0249)	0.2604*** (0.0246)
	Pop. Density	0.0001 (0.0014)	-0.0002 (0.0014)
Regime Two Parameters	Constant	5.214*** (0.5154)	5.3680*** (0.4875)
	GDP/Capita	-0.1864*** (0.0363)	-0.1960*** (0.0317)
	Pop. Density	-0.0399*** (0.0098)	-0.0510*** (0.0046)
	Own Dep. NO_x	-0.1493*** (0.0191)	-0.1441*** (0.0186)
	NO_x Spillins	-0.0794*** (0.0101)	-0.0757*** (0.0104)
	Log Likelihood	878.02	872.56
	χ^2	10.907***	
	(d.f.)	1	
	Comparison	Model 2	

*Indicates the parameter is significant at a p-value of 0.1. ** Significant at a p-value of 0.05.
*** Significant at a p-value of 0.01.
Models 1 and 2 were estimated jointly with the sulfur model with contemporaneous correlation between random effects and errors.

Table 3. Elasticity Estimates

Variable	Elasticity SO_2 Model	Elasticity NO_x Model	Means SO_2 Model		Means NO_x Model	
			Emissions	Variable	Emissions	Variable
Income Regime 1	0.65	0.63	5.17	4.58	2.20	5.49
Income Regime 2	-1.18	0.19	4.45	13.52	5.10	14.09
Population Density Regime 1	-0.02	0.001	5.17	34.13	2.20	38.46
Population Density Regime 2	0.015	-0.09	4.45	42.24	5.10	11.21
Own Deposition Factor	-0.85	-0.49	4.45	19.81	5.10	16.67
Spillovers	-0.19	-0.17	4.45	20.09	5.10	11.04
Switching Point Elasticities						
Variable	Elasticity SO_2	Elasticity NO_x	Switching Point Estimate	Variable Mean	Switching Point Estimate	Variable Mean
Population Density	0.012	0.008	11.09	35.48	12.01	13.48
Own Deposition Factor	0.14	-0.11	11.09	19.60	12.01	13.49
Spillovers	0.024	-0.003	11.09	18.71	12.01	10.23

Elasticities are in terms of %Δemissions per capita over %Δ in variable.
*** Indicates statistical significance of the variable in the model at the p-value 0.01. (see tables 1 and 2).
Units: emissions in Mt/100 people, income in $1000/person, population density in persons/10ha, own deposition factor in %, pollution deposition in t/1000 ha.

6. Summary and Conclusions

We conclude by addressing the issues raised at the outset: (1) Do different pollution types manifest different responses to changes in national income? (2) How does the publicness of different pollution types affect willingness of jurisdictions to abate them? (3) How does publicness relate to the income-pollution response or environmental Kuznet's curve? The theoretical results suggest that publicness should affect how jurisdictions abate pollution. The empirical results broadly support this. They also support the theoretical model results presented in section three with some qualifications. The estimated empirical relationship supports a Kuznets relationship between income and pollution for sulfur dioxide, showing that emissions per capita tends to increase towards a critical point and then to decline. However, for nitrogen oxides there is still an positive relationship between emissions per capita and income in regime two, although significantly less than in regime one. Hence, pollution types with different dispersion patterns or levels of publicness have different emission-income relationships.

The results also support the hypothesis that more widely dispersed pollution tends to be abated less than more local pollution. This is shown in two ways. First, the switching point for nitrogen oxides – the more widely dispersed pollutant – occurs at a higher level of income than that for sulfur dioxide (see chi-square test in tables 1 and 2). Of course, other factors could be at work. For example, Sandler and Sargent (1996) suggest that NO_x emissions have not been cut back to the same extent as SO_2 emissions in Europe because the NO_x emissions are due to a large number of small polluters. In 1990, 60.4% of SO_2 emissions in OECD countries came from power plants, 35.4% from other stationary sources and only 4.2% came from mobile sources. However, only 25% of NO_x emissions came from power plants, 22% came from other large stationary sources and 53% came from mobile sources in the transport sector.[6] It thus appears that free riding occurs both within countries and across countries for NO_x but only across countries for SO_2. Hence, free riding takes place at different levels of jurisdiction and to varying degrees at these different levels as hypothesized. Second, countries with higher own deposition factors for sulfur dioxide and nitrogen oxides tended to have lower emissions. The one qualification is that countries with higher own deposition factors and spillovers of sulfur dioxide tended to extend the switch point (at which emissions begin to decline with income) to higher levels of income.

Our results also relate to the debate over economic growth, trade and the environment. In response to criticisms of trade - led growth, which was thought to create worsening environmental conditions, empirical analyses showed that in general, "richer is cleaner," thus supporting more liberalized trade. The empirical evidence presented here lends some credence to this view. However it also yields a caution. First, most of the countries of the world are still on the upward sloping portion of the emissions income curve analyses (Selden and Song 1994). Second, even after emissions decline in the richest countries, they remain the highest emitters per capita in the world. Even if emissions in the richest countries continue to show a downward trend, the developing countries have higher population densities which tend to delay abatement and increase emissions per capita, at least in the case of sulfur dioxide.

Finally, these results highlight the difficulties in crafting effective international agreements for transboundary environmental problems if nations tend to place higher priority on local environmental problems than on global ones. This basic incentive structure may lead to a differential impact on the innovation of rules or mechanisms that place constraints on the

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[6] Source: OECD 1995 Environmental Data Compendium and author's own calculations.

behavior of agents for pollution control both within and across nations. The number and heterogeneity of agents across multiple jurisdictions will make the collective action problem of constructing rules, penalties and enforcement schemes more difficult for the most widely dispersed pollutants, leading to a bias toward stricter rules for less widely dispersed pollution occurring mainly at local levels of jurisdiction. Too much emphasis on local and insufficient emphasis on global environmental problems, raises the stakes for those seeking institutional solutions to truly global commons dilemmas.

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Appendix A: Theory

Proof of Propositions 1-3.

First, note that the individual agent utility maximization problem (4)-(7) may be re-written in the following form:

$$\max_{C^j, e_1^j, e_2^j} u^{i_j}\left(C^j - c^{-i_j}, \alpha_1^{i_j j} e_1^j + E_1^{-i_j}, \alpha_2^{i_j j} e_2^j + E_2^{-i_j}\right) \tag{A1}$$

s.t.

$$c^{-i_j} \le C^j \tag{A2}$$

$$C^j \le \omega^{i_j} + c^{-i_j} \tag{A3}$$

$$C^j \le f^c\left(e_1^j, e_2^j, \omega^{i_j} + \omega^{-i_j}\right) \tag{A4}$$

$$e_k^j \le h_k\left(C^j, q_k^{-i_j}, \omega^j\right), \; k = 1,2 \tag{A5}$$

for all i_j where we obtain ω^{-i_j} implicitly from $c^{-i_j} = f^c\left(e_1^{-i_j}, e_2^{-i_j}, \omega^{-i_j}\right)$ or $\omega^{-i_j} = f^{-\omega}\left(e_1^{-i_j}, e_2^{-i_j}, c^{-i_j}\right)$ and where $q_k^{-i_j}$ satisfies $e_k^{-i_j} = h_k\left(c^{-i_j}, q_k^{-i_j}, \omega^j\right)$. The function $f^{-\omega}$ is an inverse mapping from c to ω given any $\left(e_1^{-i_j}, e_2^{-i_j}\right)$. The function is strictly increasing in c since f_c is strictly increasing in ω. Note that $c^{i_j} = C^j - c^{-i_j}$. Hence, if $c^{-i_j} = C^j$ in (A2) then for individual i_j, $c^{i_j} = 0$. Since u^{i_j} is strictly increasing in c, constraint (A4) will be satisfied with equality. Therefore (A4) may be dropped and (A2),(A3) and (A5) replaced with:

$$c^{-i_j} \le f^c\left(e_1^j, e_2^j, \omega^{i_j} + \omega^{-i_j}\right) \tag{A2'}$$

$$f^c\left(e_1^j, e_2^j, \omega^{i_j} + \omega^{-i_j}\right) \le \omega^{i_j} + c^{-i_j} \tag{A3'}$$

$$e_k^j \le h_k\left(f^c\left(e_1^j, e_2^j, \omega^{i_j} + \omega^{-i_j}\right), q_k^{-i_j}\right), \quad k = 1,2 \tag{A5'}$$

We want to derive comparative statics results for each jurisdiction *j*. To simplify the analysis we will assume that each individual i_j within a jurisdiction *j* is identical both in preferences $u^{i_j} = u$, income $\omega^{i_j} = \omega^j$ and dispersion coefficients for each pollutant, $\alpha_k^{i_j j} = \alpha_k^{oj}$ and $E_k^{-i_j} = E_k^{-j}$. We will also assume that there is a single, stable symmetric equilibrium within a jurisdiction. Let

$$\begin{aligned} V\left(e_1^j, e_2^j, \rho^j\right) &= v\left(f^c\left(e_1^j, e_2^j, \rho^j\right), e_1^j, e_2^j, \rho^j\right) \\ &= u\left(f^c\left(e_1^j, e_2^j, I^j \omega\right) - c^{-j}, \alpha_1^{oj} e_1^j + E_1^{-j}, \alpha_2^{oj} e_2^j + E_2^{-j}\right) \end{aligned}$$

where c^{-j} corresponds c^{-i_j} and $\rho^j = \left\{\omega^j, I^j, \alpha_1^{oj}, \alpha_2^{oj}, E_1^{-j}, E_2^{-j}, c^{-j}\right\}$. If constraint (A3) or (A3') is binding then the agent is consuming all of his endowment and thus contributing nothing to the abatement of pollution. If (A5) or (A5') is satisfied with equality for $k = 1$ or $k = 2$ then the individual is not contributing to abatement of pollution types 1 or 2 respectively. If an individual is contributing to abatement then constraints (A2'),(A3'), and (A5') are non-binding constraints and we have an interior solution. Assuming that all individuals are contributing to abatement of both types of pollution, the first order conditions for the individual's problem are:

$$V_1 = u_c f_{e_1}^c + u_1 \alpha_1^{oj} = 0 \qquad \text{(A6)}$$

$$V = u_c f_{e_2}^c + u_2 \alpha_1^{oj} = 0 \qquad \text{(A7)}$$

where we use the notation $u_c = \partial u / \partial c$, $u_k = \partial u / \partial e_k$, and $f_{e_k}^c = \partial f^c / \partial e_k$. Denote the Hessian for this problem $D^2 V\left(e_1, e_2, \rho^j\right)$ which is negative semi-definite.

Suppressing the superscripts, let

$$\phi(\rho) = V\left(f^c\left(e_1(\rho), e_2(\rho)\right) / I, e_1(\rho), e_2(\rho), \rho\right)$$

$$\text{and } U(e_1, e_2, \rho) = V(e_1, e_2, \rho) - \phi(\rho)$$

where U is the primal-dual objective function. In an equilibrium, all individuals are maximizing utility given every other individuals choices of consumption and emissions levels. Since, for any given ρ, $\phi(\rho)$ represents the maximum utility attainable then $U(e_1, e_2, \rho)$ has a maximum of 0 at $(e_1(\rho), e_2(\rho))$. Differentiating $U(e_1, e_2, \rho)$ with respect to (e_1, e_2) yields the first order conditions (A6) and (A7). Differentiating with respect to ρ_κ, where ρ_κ is one of $\left(c^{-i_j}, e_1^{-i_j}, e_2^{-i_j}, E_1^{-i_j}, E_2^{-i_j}, \omega^{i_j}, \alpha_1^{i_j}, \alpha_2^{i_j}\right)$, yields the envelope result:

$$U_{\rho_\kappa} = V_{\rho_\kappa} - \phi_{\rho_\kappa} = 0 \qquad \text{(A8)}$$

The derivative V_{ρ_κ} is defined $V_{\rho_\kappa} = u_c \dfrac{\partial f_c}{\partial \rho_\kappa} + v_{\rho_\kappa}$. Second order sufficient conditions for a maximum of the primal-dual objective function, with choice variables (e_1, e_2, ρ_κ), require that the matrix:

$$D^2U(e_1, e_2, \rho) = \begin{pmatrix} V_{11} & V_{12} & V_{1\rho_\kappa} \\ V_{21} & V_{22} & V_{2\rho_\kappa} \\ V_{1\rho_\kappa} & V_{2\rho_\kappa} & V_{\rho_\kappa\rho_\kappa} - \phi_{\rho_\kappa\rho_\kappa} \end{pmatrix} \qquad \text{(A9)}$$

be negative definite. The second derivative $V_{\rho_\kappa\rho_\kappa}$ is

$$V_{\rho_\kappa\rho_\kappa} = u_{cc}\left(f^c_{\rho_\kappa}\right)^2 + 2v_{c\rho_\kappa} f^c_{\rho_\kappa} + u_c\left(f^c_{\rho_\kappa\rho_\kappa}\right) + v_{\rho_\kappa\rho_\kappa}.$$

Differentiating the first order condition (A8) with respect to ρ_κ with $e_1(\rho)$ and $e_2(\rho)$ substituted for e_1 and e_2, yields an equation from which the comparative statics results are derived:

$$
\begin{aligned}
U_{\rho_\kappa\rho_\kappa} &= \left[u_{cc}\left(f_{e_1}^{c}\frac{\partial e_1}{\partial \rho_\kappa}+f_{e_2}^{c}\frac{\partial e_2}{\partial \rho_k}+f_{\rho_\kappa}^{c}\right)+u_{cE_1}\alpha_1\frac{\partial e_1}{\partial \rho_k}+u_{cE_2}\alpha_2\frac{\partial e_2}{\partial \rho_k}+v_{c\rho_k}\right]f_{\rho_\kappa}^{c}\\
&\quad +u_c\left[f_{\rho_\kappa e_1}^{c}\frac{\partial e_1}{\partial \rho_k}+f_{\rho_\kappa e_2}^{c}\frac{\partial e_2}{\partial \rho_k}+f_{\rho_\kappa\rho_\kappa}^{c}\right]+v_{\rho_\kappa c}\left[f_{e_1}^{c}\frac{\partial e_1}{\partial \rho_k}+f_{e_2}^{c}\frac{\partial e_2}{\partial \rho_k}+f_{\rho_k}^{c}\right]\\
&\quad +v_{\rho_\kappa E_1}\alpha_1\frac{\partial e_1}{\partial \rho_k}+v_{\rho_\kappa E_2}\alpha_2\frac{\partial e_2}{\partial \rho_k}+v_{\rho_\kappa\rho_\kappa}-\phi_{\rho_\kappa\rho_\kappa}\\
&\equiv 0
\end{aligned}
$$

This equation can be rearranged to yield:

$$
\begin{aligned}
V_{\rho_\kappa\rho_\kappa}-\phi_{\rho_\kappa\rho_\kappa} &= u_{cc}\left(f_{\rho_\kappa}^{c}\right)^2+2v_{c\rho_\kappa}f_{\rho_\kappa}^{c}+u_c\left(f_{\rho_\kappa\rho_\kappa}^{c}\right)+v_{\rho_\kappa\rho_\kappa}-\phi_{\rho_\kappa\rho_\kappa}\\
&= -\left[\left(u_{cc}f_{e_1}^{c}+u_{c1}\alpha_1\right)f_{\rho_\kappa}^{c}+u_cf_{\rho_\kappa e_1}^{c}+v_{\rho_\kappa c}f_{e_1}^{c}+v_{\rho_\kappa E_1}\alpha_1\right]\frac{\partial e_1}{\partial \rho_\kappa}\\
&\quad -\left[\left(u_{cc}f_{e_2}^{c}+u_{c2}\alpha_2\right)f_{\rho_\kappa}^{c}+u_cf_{\rho_\kappa e_2}^{c}+v_{\rho_k c}f_{e_2}^{c}+v_{\rho_\kappa E_2}\alpha_2\right]\frac{\partial e_2}{\partial \rho_k}\\
&< 0
\end{aligned}
\tag{A10}
$$

where the inequality follows from the fact that D^2U is negative definite. Furthermore, $f_{e_k}^{c}=\alpha_k\left(-\frac{u_{E_k}}{u_c}\right)$, $k=1,2$ so that the terms $u_{cc}f_{e_k}^{c}+u_{cE_k}\alpha_k$ may be simplified:

$$
u_{cc}f_{e_k}^{c}+u_{ck}\alpha_k=-u_{cc}\frac{u_k}{u_c}\alpha_k+u_{ck}\alpha_k=-\alpha_k u_c\left(\frac{-u_{ck}u_c+u_{cc}u_k}{u_c^2}\right)=-\alpha_k u_c\left(\frac{\partial(-u_k/u_c)}{\partial c}\right)
$$

Hence,

$$
\begin{aligned}
V_{\rho_\kappa\rho_\kappa}-\phi_{\rho_\kappa\rho_\kappa} = &-\left[-\alpha_1u_c\frac{\partial(-u_1/u_c)}{\partial c}f_{\rho_\kappa}^{c}+u_cf_{\rho_\kappa e_1}^{c}+v_{\rho_k c}f_{e_1}^{c}+v_{\rho_k E_1}\alpha_1\right]\frac{\partial e_1}{\partial \rho_\kappa}\\
&-\left[-\alpha_2u_c\frac{\partial(-u_2/u_c)}{\partial c}f_{\rho_\kappa}^{c}+u_cf_{\rho_\kappa e_2}^{c}+v_{\rho_\kappa c}f_{e_2}^{c}+v_{\rho_\kappa E_2}\alpha_2\right]\frac{\partial e_2}{\partial \rho_\kappa}<0
\end{aligned}
\tag{A11}
$$

Proof of Proposition 1

For proposition 1i), $\rho_k=\omega^j$, $u_\omega=0$. Hence, the last two terms in the square brackets of (A11) are zero in this case. Since we assumed $\partial\left(-u_{E_k}/u_c\right)/\partial c$ >0, and $f_{\omega e_k}^{c}\le 0$ for $k=1,2$ and since

$f_{\omega}^{c} > 0$ the terms in the brackets are negative. Hence the whole expression is positive unless at least one of $\partial e_1/\partial\omega^j$ and $\partial e_2/\partial\omega^j$ are less than zero (i.e. $\partial e_1/\partial\omega^j < 0$ or $\partial e_2/\partial\omega^j < 0$). This concludes the proof of proposition 1i). For part ii), there are no contributors to abatement by assumption. Hence, $c^{i_j} = \omega^j$, and $q_k^{i_j} = 0$ for $k = 1,2$ for all individuals. Clearly an increase in ω^j will increase consumption for all individuals and hence overall consumption C^j. Since, $e_k^j \geq h_k\left(C^j, Q_k^j, \omega^j\right) = h_k\left(C^j, 0, \omega^j\right)$ and $h_k\left(C^j, Q_k^j, \omega^j\right)$ is increasing in C^j the conclusion follows. This concludes the proof of proposition 1.

Proof of Proposition 2

For $\rho_\kappa = \alpha_m^{jj}$, $\partial f^c/\alpha_m^{jj} = 0$, $m = 1,2$. Therefore the first two terms in the square brackets of (A11) are zero. In addition, $u_{\alpha_k} = u_{E_k} e_k$ and therefore

$$-v_{\alpha_k c}\frac{\partial f_c}{\partial e_m} - v_{\alpha_k E_m}\alpha_m = -u_{E_k c} e_k\left(-\frac{u_{E_m}}{u_c}\alpha_m\right) - u_{E_k E_m} e_k \alpha_m = e_k \alpha_m u_c \frac{\partial\left(-u_{E_k}/u_c\right)}{\partial E_m} \geq 0 \quad \text{(A12)}$$

for $k = 1,2$ and $m = 1,2$. The inequality follows from the assumption $\dfrac{\partial\left(-u_{E_k}/u_c\right)}{\partial E_m} \geq 0$ where the inequality is strict if $k = m$. Therefore, both of the terms in the square brackets of (A11) are positive. Hence, $\partial e_1/\partial\alpha_k^{jj} < 0$ or $\partial e_2/\partial\alpha_k^{jj} < 0$ for $k = 1,2$. For $\rho_\kappa = E_m^{-j}$, $\partial f_c/E_m^{-j} = 0$, $m = 1,2$. Therefore the first two terms in the square brackets of (A11) are zero. In addition, $v_{E_k^{-j}} = u_{E_k}$ and therefore

$$-v_{E_k^{-j}c}\frac{\partial f_c}{\partial e_m} - v_{E_k^{-j}E_m}\alpha_m = -u_{E_k c}\left(-\frac{u_{E_m}}{u_c}\alpha_m\right) - u_{E_k E_m}\alpha_m = \alpha_m u_c \frac{\partial\left(-u_{E_m}/u_c\right)}{\partial E_k} \geq 0 \quad \text{(A13)}$$

for $k=1,2$ and $m=1,2$. Hence, $\partial e_1 \big/ \partial E_k^{-j} < 0$ or $\partial e_2 \big/ \partial E_k^{-j} < 0$. This concludes the proof of proposition 2.

Proof of Proposition 3

For proposition 4, first consider $\rho_\kappa = \alpha_m^{jj}$. Since $\dfrac{\partial\left(-u_{E_k} / u_c\right)}{\partial E_m} = 0$ by additive separability, $m \neq k$ the expressions (A12) and (A13) are zero for $m \neq k$. Since the expressions (A12) and (A13) are positive for $m=k$ then it is clear from (A11) that $\partial e_k \big/ \partial \alpha_k^{jj} < 0$ and $\partial e_k \big/ \partial E_k^{-j} < 0$ for $k=1,2$.

Proof Sketch of Proposition 4. *Comparatives statics on population.*

To prove that $\tilde{e}_k^j > e_k^j$, $\tilde{C}^j > C^j$ and $\tilde{Q}_k^j > Q_k^j$ if $\tilde{I}^j > I^j$ $k=1,2$ note that for I^j or $\tilde{I}^j$, the equilibrium conditions $-\dfrac{u_k}{u_c}\left(c^j, E_k^j\right) = \dfrac{\kappa_k}{\alpha_k^{jj}} = -\dfrac{u_k}{u_c}\left(\tilde{c}^j, \tilde{E}_k^j\right)$ (see equation 8) are assumed to be satisfied for $k=1,2$. Here κ_k is a constant, where $\dfrac{\partial f^c}{\partial e_k^j} = \kappa_k$ because of the assumption of linear technologies. By the assumption that pollution is a normal good, if $c^j > \tilde{c}^j$ then $E_k^j < \tilde{E}_k^j$. To prove $\tilde{e}_k^j > e_k^j$ suppose, without loss of generality, that $\tilde{e}_1^j \leq e_1^j$. Then by the pollution consumption equation $E_k^{-j} = E_k^j - \alpha_k^{jj} e_k^j$ or $E_k^j = \alpha_k^{jj} e_k^j + E_k^{-j}$ it is clear that $\tilde{E}_1^j \leq E_1^j$ since by assumption every parameter is unchanged except I^j. Hence, for the above equilibrium condition to hold $\tilde{c}^j \geq c^j$ which implies $\tilde{q}_1^j + \tilde{q}_2^j \leq q_1^j + q_2^j$ by the budget constraint for each individual. This also implies that $\tilde{E}_2^j \leq E_2^j$ by the equilibrium condition and the conditions on the utility function. Since $\tilde{q}_k^j = \tilde{Q}_k^j \big/ \tilde{I}^j$ for $k=1,2$ we have $\dfrac{\tilde{Q}_1^i}{\tilde{I}^j} \leq \dfrac{Q_1^j}{I^j}$ or $\dfrac{\tilde{Q}_2^i}{\tilde{I}^j} \leq \dfrac{Q_2^j}{I^j}$. This implies

$$\tilde{e}_k^j = \tilde{I}^j\left(\beta_k \tilde{c}^j - \theta_k \frac{\tilde{Q}_k^j}{\tilde{I}^j}\right) > \left(\beta_k c^j - \theta_k \frac{\tilde{Q}_k^j}{I^j}\right) I^j = e_k^j$$

for at least one $k = 1,2$. Then $\tilde{E}_k^j > E_k^j$, which is a contradiction.

Hence $\tilde{e}_k^j > e_k^j$ and $\tilde{E}_k^j > E_k^j$ for , $k = 1,2$ which by the equilibrium condition means that $\tilde{c}^j < c^j$. This also means that $\tilde{q}_1^j = \frac{\tilde{Q}_1^j}{\tilde{I}^j} > \frac{Q_1^j}{I^j} = q_1^j$ or $\tilde{q}_2^j > q_2^j$ and $\frac{\tilde{e}_k^j}{\tilde{I}^j} = \beta_k \tilde{c}^j - \theta_k \tilde{q}_k^j < \beta_k c^j - \theta_k q_k^j$ $= \frac{e_k^J}{I^j}$ for at least one $k = 1,2$.

Proof of Proposition 5.

To prove proposition 6 assume that $\hat{\omega}^j \geq \overline{\omega}^j$. Suppose $\tilde{\omega}^j$ is such that $\hat{\omega}^j \geq \tilde{\omega}^j \geq \overline{\omega}^j$ and let $\left(\tilde{C}^j, \tilde{Q}^j, \tilde{E}^j, \tilde{e}^j\right)$ be the equilibrium allocation for $\tilde{\omega}^j$ when the parameter vector is $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ and let $\left(\hat{C}^j, \hat{Q}^j, \hat{E}^j, \hat{e}^j\right)$ be the equilibrium allocation for $\hat{\omega}^j$ when $\left(\hat{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$, $\left(\overline{\alpha}_1^{jj}, \hat{E}_1^{-j}, \bar{I}^j\right)$ or $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \hat{I}^j\right)$. At $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ and $\tilde{\omega}^j$ the equilibrium allocation $\left(\tilde{C}^j, \tilde{Q}^j, \tilde{E}^j, \tilde{e}^j\right)$ satisfies:

$$-\overline{\alpha}_1^{jj}(\beta_1 + \theta_1)\frac{u_1}{u_c} - \alpha_2^{jj}\beta_2 \frac{u_2}{u_c} = 1 \qquad \text{(A14)}$$

with $\tilde{Q}_1^j \geq 0$ and $\tilde{q}_1^{i_j} \geq 0$ for each individual in the jurisdiction. The equation (A14) is an the equilibrium condition which can be derived by rearranging the first order condition for $q_1^{i_j}$ for problem (4)-(7) in the text . The equilibrium condition is satisfied with equality because for $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ the wealth level $\overline{\omega}^j$ is the critical one and since $\tilde{\omega}^j \geq \overline{\omega}^j$ the equilibrium allocation for $\tilde{\omega}^j$ must satisfy the condition with equality because $Q_1^j = \sum_{i_j} q_1^{i_j}$ is increasing in ω^j for $\omega^j \geq \overline{\omega}^j$. At $\left(\hat{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ we have

$$-\hat{\alpha}_1^{jj}(\beta_1+\theta_1)\frac{u_1}{u_c} - \alpha_2^{jj}\beta_2\frac{u_2}{u_c} \leq 1 \tag{A15}$$

and $\hat{Q}_1^j = 0$ since $\hat{Q}_1^j$ is an allocation for $\hat{\omega}^j$ and $\hat{\omega}^j$ is the critical wealth level. We have this inequality also at $\left(\overline{\alpha}_1^{jj}, \hat{E}_1^{-j}, \bar{I}^j\right)$ or $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \hat{I}^j\right)$. Since $\tilde{Q}_1^j \geq 0$ in (A14) we have $\tilde{C}^j \leq \bar{I}^j\tilde{\omega}^j$ and $\tilde{e}_k^j \leq \beta_k \bar{I}^j\tilde{\omega}^j$ for $k=1,2$. At $\left(\hat{\alpha}_1^{jj}, \overline{E}_1^{-j}, \bar{I}^j\right)$ and $\hat{\omega}^j$, we have $\hat{C}^j = \bar{I}^j\hat{\omega}^j > \bar{I}^j\tilde{\omega}^j \geq \overline{C}^j$ and $\hat{e}_k^j = \beta_k\bar{I}^j\hat{\omega}^j > \beta_k\bar{I}^j\tilde{\omega}^j \geq \bar{e}_k^j$. Hence, $\hat{E}_k^j > \overline{E}_k^j$ for $k=1,2$ since $\hat{\alpha}_1^{jj}\hat{e}_1^j + \overline{E}_1^{-j} > \alpha_1^{jj}\bar{e}_1^j + \overline{E}_1^{-j}$ and $\alpha_2^{jj}\hat{e}_2^j + E_2^{-j} > \alpha_2^{jj}\bar{e}_2^j + E_2^{-j}$. At $\left(\overline{\alpha}_1^{jj}, \hat{E}_1^{-j}, \bar{I}^j\right)$ we have the same result since $\hat{e}_k^j = \beta_k\bar{I}^j\hat{\omega}^j > \beta_k\bar{I}^j\tilde{\omega}^j \geq \bar{e}_k^j$ for $k=1,2$ and $\overline{\alpha}_1^{jj}\hat{e}_1^j + \hat{E}_1^{-j} > \alpha_1^{jj}\bar{e}_1^j + \overline{E}_1^{-j}$. At $\left(\overline{\alpha}_1^{jj}, \overline{E}_1^{-j}, \hat{I}^j\right)$ we also have the same result since $\hat{e}_k^j = \beta_k\hat{I}^j\hat{\omega}^j > \beta_k\bar{I}^j\tilde{\omega} \geq \bar{e}_k^j$ for $k=1,2$. Hence in all three cases $\hat{C}^j > \overline{C}^j$ and $\hat{E}_k^j > \overline{E}_k^j$ for $k=1,2$. Let $c^j = C^j/I^j$. Then $-\frac{u_k}{u_c}\left(\hat{\omega}^j, \hat{E}_k^j\right) > -\frac{u_k}{u_c}\left(\overline{C}^j\big/\bar{I}^j, \overline{E}_k^j\right)$ for $k=1,2$ and it follows that:

$$-\overline{\alpha}_1^{jj}(\beta_1+\theta_1)\frac{u_1}{u_c}\left(\hat{\omega}^j, \hat{E}_1^j\right) - \alpha_2^{jj}\beta_2\frac{u_2}{u_c}\left(\hat{\omega}^j, \hat{E}_2^j\right) > -\overline{\alpha}_1^{jj}(\beta_1+\theta_1)\frac{u_1}{u_c}\left(\bar{c}^j, \overline{E}_1^j\right) - \alpha_2^{jj}\beta_2\frac{u_2}{u_c}\left(\bar{c}^j, \overline{E}_2^j\right) = 1$$

which is also true when $\overline{\alpha}_1^{jj}$ is replaced with $\hat{\alpha}_1^{jj}$. This is a contradiction of (A15). Hence $\hat{\omega}^j < \overline{\omega}^j$. This concludes the proof.

Appendix B: Data

Total emissions of sulfur dioxide and nitrogen oxides came from several sources.[1] For European countries the data was taken from EMEP, as published in Barrett et. al. (1995), Europe's cooperative program for monitoring transboundary pollution. These data are also found in the OECD 1993 and 1995 Environmental Data Compendiums, which also include data for the United States, Canada, and Japan. The longest series for an individual country that is available from these data is 1970, 1975 and 1980-1993. For some countries there are gaps in the series. While this would not normally present a problem for analysis, the formulation of the econometric model requires that we have estimates of emissions for all neighboring countries which have positive weights in the pollution transport matrix. Pollution estimates were computed by the methodology presented in Kato and Akimoto (1992). The procedure depends on the International Energy Agencies Energy Statistics (IEA)[2], emissions factors for various fuel types that are specific to countries and economic activities. The procedure also depends on abatement factors for various sectors and fuel types. For European countries emission factors were taken from Amann (1990), which have been used in the International Institute of Applied Systems Analysis (IIASA) model of acidification or RAINS. Emissions were then estimated for the missing years and for adjacent years, at first without adjusting for abatement. An abatement factor was imputed for the adjacent years and then a simple interpolation procedure produced the

[1] For some countries not all years were available.

abatement factor for the missing years. The abatement factor was then applied to unadjusted emissions estimates.

The data for Asian countries was taken from Kato and Akimoto (1992), which is also published in UNEP 1993/94. While the paper only provides estimates for 1975, 1980, 1985, 1986 and 1987 the procedure outlined is applicable to the data from 1970 to 1993. Hence, the procedure outlined in Kato and Akimoto (1992) was applied to Asian countries 1970, 1981-1984 and 1998-1993. The data take into account changes in fuel types toward lower sulfur content in Taiwan and Korea. The trends in these factors were maintained for 1988-1993[3]. The data also include emissions from non-ferrous metal industries. The emissions factors provided in Kato and Akimoto (1992) were based on extensive field surveys by the authors and the Research Group on the Energy Consumption in Asia and the Global Environment.

The income measure used is the real GDP per capita series from the Penn 5.6 World Tables that have been developed by Summers and Heston (1994). These data were specifically constructed for cross country comparisons and are in $1985 (US). However, the series were not complete for the years 1970, 1975, 1980-1993. For countries where the other variables were available, the Penn 5.6 world table data was supplemented with data from the World Bank Tables 1995 by indexing the World Bank GDP in constant 87 US dollars to the Penn 5.6 RGDP data. Population data was also taken from the Penn 5.6 World Tables. Population density was calculated by dividing total population by the area of the country adjusted by the percentage of

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[2] IEA energy statistics are provided in two series – Energy Statistics of OECD Countries and Energy Statistics of non-OECD countries. The IEA also publishes these data in electronic format.
[3] This was based on a personal communication with Akimoto (1997).

the area of the country that exhibits low human disturbance – a variable obtained from the World Resources Institute's World Resources Data Tables.

The source of the own deposition factors (α^{jj}) and the spillover transport matrix for European countries was EMEP. Barrett et. al. (1995) gives transport matrices for both sulfur and oxidized nitrogen for the years 1980, 1985-1993. Average transport coefficients were used for the missing years. For Canada and the United States "own deposition" and transport factors were obtained from Venkatram et. al. (1991)[4]. Transport matrices for Asian Countries are not available. To solve this problem own deposition factors and transport coefficients for Asian countries were independently estimated. Estimates for own country deposition were constructed by building a relationship between own country deposition factors and variables easily obtainable from other sources for the European and North American countries. These variables included country size, border length, length of coastline, and maritime area. An equation was estimated and then applied to the Asian countries. Estimates for emissions transport were built in a similar manner from the European and North American transport matrices, by building a relationship between the portion of a countries' emissions deposited in another country and other easily obtainable variables. These variables were the shortest distance between the two countries, size of each country, length of the border between the two countries, the perimeters of the two countries, and downwind dummy variables.

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[4] In NAPAP Report 8, Section 4 in Acidic Deposition: State of Science and Technology (1991).