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A Tale of Two Collectives: Sulfur Versus Nitrogen Oxides Emission Reduction in Europe

James C. Morduch[1] and Todd Sandler[2]

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A Tale of Two Collectives: Sulfur Versus Nitrogen Oxides Emission Reduction in Europe

James C. Morduch[1] and Todd Sandler[2]

University of Texas, Dallas[1]
Iowa State University[2]

and

Senior Research Fellow[2]
Institute for Policy Reform

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A theoretical model of emission reductions is specified that accounts for voluntary and nonvoluntary behavior regarding the adherence to the Helsinki and Sofia Protocols, which mandated emission reductions for sulfur and nitrogen oxides (NO_x), respectively. From the theoretical model, we derive an econometric specification for the demand for emission reductions that adjusts for the spatial dispersion of the pollutant. When tested for 26 European nations, the model and its forecasts perform reasonably well for sulfur cutbacks. Less satisfying results are obtained for NO_x. A number of factors are identified that indicate that sulfur emissions are easier to control than those of NO_x.

A TALE OF TWO COLLECTIVES:

SULFUR VERSUS NITROGEN OXIDES EMISSION REDUCTIONS IN EUROPE

Executive Summary

In this paper, we formulate a voluntary contribution model to explain the reductions in sulfur and nitrogen oxides (NO_x) emissions in Europe in the 1980s. In pre-treaty periods, the model views all reductions as voluntary, while, in post-treaty periods, the model distinguishes between mandated and voluntary reductions. The latter includes cutbacks beyond mandated levels. By depicting the decision maker as a unitary actor that has its constituency's welfare at heart, the model assumes that the collective action problem of emission reductions has been solved at the national level. At the transnational level, strategic behavior is allowed as nations rely on the emission reductions of others to substitute for their own efforts--i.e., free riding is permitted. Based on the theoretical model, we specify a nation's demand for voluntary reductions in either sulfur or NO_x emissions. This demand depends on the nation's income, the per-unit price of emission reductions, the fraction of the nation's emissions that falls on its territory, the reduction of a nation's depositions that is derived from the actions of other nations (termed a "spillin"), the target rate of emission reductions, and some country-specific environmental and political variables. Environmental factors attempt to measure pollution-specific damages, while political factors correspond to the extent of civil and political freedoms.

The empirical model and estimations account for the spatial dispersion of emissions within the European sample countries. For the 1980-90 period, spatial dispersion is tracked through measurements taken from a grid of monitoring stations established by the Cooperative Programme for Monitoring

and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP). Separate measurements are available for sulfur and NO_x.

Our theoretical and empirical analyses are applied to study the adherence to the Helsinki Protocol and the Sofia Protocol, which mandated European cutbacks in sulfur and NO_x emissions, respectively. By establishing explicit targets for cutbacks, these two protocols strengthened the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP), which merely set up the framework for studying a number of air pollutants (sulfur, NO_x, and volatile organic compounds) with the intention of fixing future limits.

Two different results emerge when the econometric model is applied to a sample of 26 nations that includes market and transitional economies. For sulfur reductions, the model and its forecasts perform reasonably well, thus supporting our theoretical construct. Free riding does, indeed, characterize the ratifiers of the Helsinki Protocol, since increased reductions by others induce a nation to limit its own voluntary efforts at cutbacks. Increases in income and political freedoms augment emission reductions. This finding suggests that foreign aid and the promotion of democracy on behalf of the wealthier countries can have a dividend in terms of a better environment for all. Greater target levels limit the extent of voluntary reductions in the post-Helsinki era. Voluntary efforts are also related to the fraction of a country's sulfur deposited within its own borders. Since these fractions tend to be high for sulfur, nations are more willing to take voluntary action in reducing their sulfur emissions. Furthermore, the major contributors of sulfur pollution are public utilities that are relatively easy for a country to control. The forecasts bode well for a more stringent future protocol, because a majority of nations have already achieved reductions beyond mandated levels.

For NO_x, the model performs in a less convincing manner. This is probably due to the large number of small polluters (i.e., owners of automobiles and trucks), whose uncoordinated actions call into question our unitary decision maker assumption at the national level. Additionally, NO_x is more transferable with relatively small fractions of nations' emissions deposited on their own soil. As compared with sulfur, a much smaller proportion of the sample nations' aggregate emissions is deposited within the treaty region. In consequence, there is a greater degree of free riding regarding NO_x cutbacks as compared with sulfur at the transnational level. Increases in income and political freedoms reduce voluntary cutbacks, thus indicating that policies that favor sulfur reductions can inhibit NO_x curtailment. In the case of NO_x, greater control needs to be instituted at the national level, prior to the framing of tougher treaties. Forecasts are not optimistic in terms of stricter protocols for NO_x in the near future. In hindsight, the LRTAP Convention appears to have been properly designed when it provided for separate protocols to be enacted for the diverse pollutants.

A TALE OF TWO COLLECTIVES:

SULFUR VERSUS NITROGEN OXIDES EMISSION REDUCTION IN EUROPE*

1. INTRODUCTION

In recent years, there has been tremendous interest shown in the study of a host of transnational collective action problems including acid rain, global warming, desertification, deforestation, and stratospheric ozone depletion (see, e.g., Helm, 1991; Murdoch and Sandler, 1994a; Poterba, 1993; Runge, 1993; and Sandler and Sargent, 1995). In the current paper, we are particularly interested in collective action concerning acid rain and surface-level ozone, stemming from the emissions of sulfur (S) and nitrogen oxides (NO_x). European concern over these and other pollutants resulted in the formulation of the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP) and its later ratification on 16 March 1983.[1] Subsequent protocols to LRTAP have placed explicit limits on sulfur and NO_x emission levels. A casual comparison of European emission data for sulfur and nitrogen oxides throughout the 1980s (Sandnes, 1993, Tables 1-2) tells a different story with respect to these pollutants. Most countries have met or exceeded the 30 percent mandated reductions from 1980 levels in sulfur by the end of the decade, while some of these same countries were having a difficult time in reducing NO_x emission levels (see raw data in Table 1A of the Appendix). This suggests a conundrum, since both pollutants lead to serious environmental consequences. Why are the two responses so different? This paper attempts to answer this question by analyzing the factors behind these two seemingly similar, but different, collective action problems. An important message that derives from our analysis is to resist the temptation to lump together collective action problems even if they involve the same participants. As a collective action problem is analyzed carefully, key ingredients--group size, the range of benefit or cost spillovers, and/or selective incentives--may differ (Olson, 1965; Sandler, 1992).

This paper has five purposes. First, we formulate a theoretical model of emission reductions that includes voluntary and nonvoluntary behavior regarding sulfur and NO_x pollution.[2] Voluntary behavior concerns emission cutbacks beyond levels mandated in a protocol, whereas nonvoluntary behavior involves meeting mandated cutbacks. Second, we specify an empirical model, derived from the theoretical model, that accounts for the spatial dispersion of emissions within the European sample countries. Third, in an effort to refute the theoretical model, we place the empirical specification through a battery of tests using EMEP (Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe) data for the 1980-90 period. Fourth, we explain the above-mentioned contrast in the two transboundary pollution problems. Fifth, we use the best specification of emission reductions to forecast future reductions and comment on subsequent protocols for sulfur and NO_x.

The analysis indicates that our theoretical model leads to an empirical representation that yields reasonable results for sulfur, but less satisfying results for NO_x. Sulfur emissions appear easier to control than NO_x, because a greater proportion of a country's emissions falls on its own territory and within the treaty's region. Moreover, sulfur pollution sources are more concentrated and include public utilities that are easy for a country to control. Strategic behavior, whereby a country limits its cleanup efforts as others reduce emissions, characterizes both problems despite the enactment of conventions and protocols, but appears stronger for NO_x. In the case of sulfur, a greater demand for a cleaner environment comes about as income and political freedoms are enhanced, while an opposite picture emerges for nitrogen oxides. Forecasts suggest more stringent protocols in the near-term for sulfur, while the same is not true for NO_x.

The remainder of the paper contains six sections. Section 2 includes background information on sulfur, NO_x, and the associated international agreements. In section 3, the theoretical model is presented, while in section 4, the empirical model and data are indicated. Section 5 displays the empirical results and forecasts. Policy implications are given in section 6, and conclusions are contained in section 7.

2. BACKGROUND

When sulfur and NO_x emissions from electric generation, transportation, and other sources combine in the atmosphere with water vapor and tropospheric ozone, sulfuric and nitric acid can form. These acids can later fall with the rain and degrade lakes, rivers, coastal waters, forests, and manmade structures (Mohnen, 1988). This degradation can also stem from dry depositions of sulfur and NO_x that lead to increased acidity of soils and water sheds. Additionally, NO_x is a precursor to tropospheric ozone, which can damage human health and vegetation (OECD, 1990). Although sulfur and NO_x cause transboundary pollution, the composition of their sources differs (see OECD, 1990 for full information). In 1980, sources of sulfur emissions in percentage terms were: 47.8 from power plants; 37.4, industry; 10, residential and commercial; 3.7, mobile (e.g., cars and trucks); and 1, miscellaneous. In 1980, sources of NO_x emissions in percentage terms were: 53.6 from mobile polluters; 23.5, power plants; 15.4, industry; 6.1, residential and commercial; and 1.3, miscellaneous. These differences in sources figure prominently in our interpretation of the empirical results.

For now, we note that the primary source of sulfur emissions is power plants and that of NO_x is mobile. We also note that the effects of sulfuric and nitric acids are not the same; greater uncertainty characterizes nitric acid.

A variety of strategies are available for the control of sulfur and NO_x emissions. Both emissions can be limited through improved efficiency, especially in the case of residential and commercial uses, and increased conservation. Sulfur can also be controlled through the use of low-sulfur coal and oil as well as flue-gas desulfurization for power plants. In the case of NO_x, emissions can be reduced in power plants through the use of a fluidized bed combustion process. Pollution from mobile sources can be curtailed with catalytic converters and turbocharging of engines.

Both sulfur and NO_x emissions pose a transnational pollution concern, because once released into the atmosphere these pollutants can remain aloft for days and travel from their emission source to be deposited on the territory of a downwind country. Sulfur emissions can remain in the atmosphere for .01 days to 7 days, while NO_x can remain aloft from 2 to 8 days (Alcamo and Runca, 1986, p. 3). On average, sulfur pollutants travel shorter distances than NO_x pollutants and land nearer to home (see transport matrices in Sandnes, 1993 for verification). This can be seen in Table 2A in the Appendix when comparing the fraction of each country's emissions that are deposited either on itself (OWNSUL, OWNNOX) or within the 26-country treaty region (AREASUL, AREANOX). With one exception (the Netherlands for AREANOX), sulfur fractions far exceeded corresponding fractions for NO_x. Sulfur is less easily transferred to one's neighbors; this is a crucial observation.

To account for the transport of sulfur and NO_x among European countries, we rely on the transport matrix devised from EMEP measurements and reported for various years in Sandnes (1993).[3] For example, a sulfur matrix's entries indicate the amount of sulfur deposited in country i (row country) emitted by country j (column) country (see Table 3A of the Appendix). By dividing each entry by the emitter's total sulfur emissions and then multiplying by the fraction of the country's emissions that remains in the study area, we generate a transport matrix in which each entry indicates the <u>fraction</u> of country j's emissions deposited on country i--denoted by α_{ij}. The diagonal entries of the matrix indicate the fraction of country i's emissions dumped on itself. Bigger nations typically have larger diagonal elements than smaller countries, so that they absorb more of their own sulfur and NO_x pollutants. A similar matrix can be formulated for NO_x. Although emission entries can differ in the <u>untransformed</u> matrix by year, the transport matrix, when expressed in percentage terms, varies imperceptibly from year to year; hence, a single transport matrix can be applied to the subperiods of this study. In particular, we use the (transformed) transport matrix for 1985 throughout the empirical estimates.

One international convention and two subsequent protocols are germane to our study. On 13 November 1979, the LRTAP Convention was adopted at a high-level meeting of the UN Economic Commission for Europe on the Protection of the Environment. Signatories included Austria, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, Finland, France, East Germany, West Germany, Greece, Hungary, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Soviet Union, Spain, Sweden, Switzerland, Turkey, the UK, the US, and Yugoslavia (UNEP, 1991). For our sample in the empirical section, we exclude four countries. Canada, Iceland, and the US are left out owing to our focus on European deposition, while Liechtenstein is excluded because it does not appear in the EMEP transport matrix as the grid is too coarse. The signatories of LRTAP agreed that a serious problem exists and that further study was needed prior to specific limits of emission reductions being mandated. On 8 July 1985, the Helsinki Protocol to the LRTAP Convention was adopted and committed ratifiers to reduce sulfur emissions by at least 30 percent, based on 1980 levels, as soon as possible or by 1993. The protocol entered into force on 2 September 1987.

In the case of NO_x emissions, protocols have been much slower. On 31 October 1988, the Sofia Protocol was signed, requiring emissions of NO_x to return to 1987 levels by 31 December 1994 (UNEP, 1991). This protocol did not enter into force until 14 February 1991. We intend to explain why NO_x is more problematic for the European countries.

3. THEORETICAL MODEL

We present a simple model of voluntary and nonvoluntary emission reductions of a pollutant. The model is intentionally kept uncomplicated because our focus is on estimation and not on theoretical complexity. The underlying model is a Nash subscription model,[4] in which an impure public good (emission reduction) is allocated by a set of countries that are emitters and recipients of a pollutant (e.g., S or NO_x), henceforth, denoted as emissions. For modeling purposes, each country is represented by a unitary actor whose interests are those of the nation's citizens. This representation ignores the collective action problem at the national level, but we return to this issue when interpreting our empirical results.

The i^{th} nation's strictly increasing, quasi-concave utility function is

$$U_i = U_i(y_i, \alpha_{ii}q_i + \tilde{Q}_i, E_i), \qquad (1)$$

where y_i is the i^{th} nation's consumption of the private numéraire good; q_i denotes the i^{th} nation's reduced emissions between a base year and the current year of reference; α_{ii} is the fraction of the i^{th} nation's emissions deposited on itself; $\tilde{Q}_i$ is the reduction of emission spillins for nation i; and E_i is a vector of environmental and political factors in nation i. The term $\alpha_{ii}q_i$ indicates the reduced emissions of nation i that are no longer deposited on its soil. In general, q_i can be decomposed into two parts: a voluntary reduction, q_i^V, and a mandated reduction, q_i^T. In the case of sulfur, the Helsinki Protocol mandated targetted reductions of 30 percent of 1980 emission levels, so that voluntary reductions can be denoted by

$$q_i^V = q_i - q_i^T = 0.7\cdot(1980 \text{ emission levels}) - \text{current emissions}. \qquad (2)$$

Emission levels smaller than 70 percent of the 1980 emission level are considered to include voluntary reductions. By (2), total emission reductions in nation i, based on a base year level, equal

$$q_i = q_i^V + q_i^T \; . \qquad (3)$$

If $q_i^T = 0$ so that all reductions are voluntary, then $q_i^V = q_i$ and there is no distinction between voluntary and nonvoluntary reductions--all are voluntary.

Reduced spillins of pollution deposition in nation i, derived from <u>other</u> countries, may also be made up of voluntary and nonvoluntary emissions from neighboring countries. Suppose that there are n countries in the model. Then these spillins are

$$\tilde{Q}_i = \sum_{j\neq i}^{n} \alpha_{ij} q_j$$

$$= \sum_{j\neq i}^{n} \alpha_{ij}(q_j^V + q_j^T) \qquad (4)$$

for nation i, where α_{ij} is the fraction of nation j's emissions that fall on nation i. In (4), the index on the summation runs from j = 1 to j = n but excludes i. These spillins equal the summed reductions in transported emissions that are deposited on nation i, but that originate from other nations. Total deposition reductions, Q_i, in nation i equal $q_i + \tilde{Q}_i$, or the sum of reductions from domestic and foreign sources. If all of a country's emissions fall within the region defined by the model, then each country's emissions must be either deposited on itself or on another country within the region, so that $\sum_{i=1}^{n} \alpha_{ij} = 1$. That is, column sums of the transport matrix of the α_{ij}s must sum to one. This highlights the complete divisibility of the pollutant among nations in the case of sulfur and NO_x. Publicness arises from nonexcludability, not nonrivalry. If, instead, say 62 percent of a nation's emissions are deposited within the region and the remainder are dropped on downwind regions or dissipate into the atmosphere, then the column sums for α_{ij} equals 0.62.

Nation i is assumed to face the following linear budget constraint:

$$m_i = y_i + p_i q_i^V + p_i q_i^T , \tag{5}$$

where m_i is national income, the price of the private good is unity, and p_i is the per-unit price of voluntary and nonvoluntary reductions. Inasmuch as price data on emission reductions is limited and must be proxied, we keep the model uncomplex--p_i does not differ between the two classes of emission reductions, and a parametric price is assumed. With the use of equations (3)-(4), we can now state the maximization (subscription) problem for nation i:

$$\max_{q_i^V} U_i(y_i,\ \alpha_{ii} q_i^V + \alpha_{ii} q_i^T + \sum_{j \neq i}^{n} \alpha_{ij}(q_j^V + q_j^T),\ E_i)$$

$$\text{subject to:} \begin{cases} m_i = y_i + p_i q_i^V + p_i q_i^T \\ \tilde{Q}_i \text{ and } q_i^T \text{ given} \\ q_i^V \gtreqless 0. \end{cases}$$

A number of remarks are in order concerning the optimization problem. First, this is a Nash representation so that each nation chooses its optimizing response assuming the best-response level of spillins, $\tilde{Q}_i$. A Nash equilibrium results when each nation in the model is optimized, given its counterparts' best response, and would not unilaterally wish a different level of q_i^V. Second, if nonvoluntary or targetted q_i^T exists, then it is exogenous. Third, the choice variable, q_i^V, can be positive, negative, or zero; positive (negative) levels indicate greater (smaller) reductions than mandated. Voluntary reductions are, thus, unconstrained in terms of its sign, so that only the budget constraint and the exogenous levels of $\tilde{Q}_i$ and q_i^T constrain the problem. Fourth, exogenous factors include m_i, p_i, α_{ii}, q_i^T, $\tilde{Q}_i$, and E_i. As discussed in section 4, E_i represents both environmental and political factors and acts as a shift variable. Environmental factors can include proxies for pollution damage--e.g., tree losses in the case of sulfur emissions and population density in the case of NO_x. Political factors in terms of freedom and civil liberties can also influence the nation's decision making choice of q_i^V. Autocracies, for example, may be less mindful of the environmental assets and less pressured by their citizens to preserve these assets (Congleton, 1992). Fifth, if mandated levels are zero, then the choice variable is q_i, and q_i^T is no longer an exogenous variable. Furthermore, the target level would then not be part of spillins--spillins would only be voluntary.

From the first-order conditions of the optimization problem, we can express the i^{th} nation's demand for q_i^V, in terms of the exogenous variables, as

$$q_i^V = q_i^V(m_i,\ p_i,\ \alpha_{ii},\ E_i,\ \sum_{j\neq i}^{n}\alpha_{ij}(q_j^V + q_j^T),\ q_i^T),\ \text{for } q_i^T > 0, \tag{6}$$

and

$$q_i^V = q_i^V(m_i,\ p_i,\ \alpha_{ii},\ E_i,\ \sum_{j\neq i}^{n}\alpha_{ij}q_j^V),\ \text{for } q_i^T = 0. \tag{7}$$

Because the latter is a special case of the former, we focus our remarks on the empirical representation of the demand equation in (6). This equation applies to <u>each</u> country in the region (model). Taking a Taylor series expansion and keeping just the linear terms we have

$$q_i^V = \beta_0 + \rho \sum_{j \neq i}^{n} \alpha_{ij}(q_j^V + q_j^T) + \beta_1 m_i + \beta_2 p_i + \beta_3 \alpha_{ii} + \beta_4 E_i + \gamma q_i^T + \epsilon_i \qquad i = 1,\ldots,n \qquad (8)$$

where β_0 is a constant, β_is are coefficients, ϵ_i is an error (remainder) term, and ρ and γ are coefficients.

To simplify notation, we revert to a vector representation where q^V is the n x 1 vector $(q_1^V,\ldots,q_n^V)'$; q^T is the n x 1 vector $(q_1^T,\ldots,q_n^T)'$, $\tilde{A}$ is an n x n transport matrix, X is an n x 5 matrix of parameters, β is a 5 x 1 vector $(\beta_0,\ldots,\beta_4)'$, and ϵ is an n x 1 vector $(\epsilon_1,\ldots,\epsilon_n)'$ of error terms. The i^{th} row of the X matrix is $(1, m_i, p_i, \alpha_{ii}, E_i)$. Finally, we must distinguish the A transport matrix from the $\tilde{A}$ transport matrix. The latter includes zeros in the diagonal places, so that a country's q_i^V only appears on the left-hand side of its equation. The remaining terms in $\tilde{A}$ are the α_{ij}s. Thus, the equation system in (8) can be written in matrix form as

$$q^V = \rho\tilde{A}q^V + X\beta + \rho\tilde{A}q^T + \gamma q^T + \epsilon, \qquad (9)$$

where the targetted reductions affect spillins, through the definition of spillins, and where these reductions have an independent influence owing to q_i^T in each country's optimization problem. Equation (9) is estimated below for European nations in regards to the Helsinki and Sofia Protocols.

4. EMPIRICAL MODEL

Equation (6) is a representation of a country's demand function for emission reductions. We hypothesize that the data observed in the real world are generated from this type of behavioral relationship and that the relationship provides a good prediction of future behavior. To test this assumption, we attempt to refute it. Our methodology involves using observations on the relevant variables to estimate the parameters as approximations to the function, such as the one presented in equation (8). These parameter estimates (the βs, ρ, and γ) can then be checked for logical consistency when interpreted as demand function parameters. Additionally, we can use the estimated relationships for forecasting future behavior and then measure the accuracy of the forecasts. Serious violations of the demand function interpretation or of the forecasts suggests refuting the hypothesis.

Looking at equation (6), we see that q_i^V depends on the i^{th} nation's income (m_i), the price per unit of emission reductions (p_i), the fraction of i's emissions that fall within its own borders (α_{ii}), the reduction of i's depositions derived from the actions of other nations $[\tilde{Q}_i = \sum_{j \neq i}^{n} \alpha_{ij}(q_j^V + q_j^T)]$, the target rate of emission reductions (q_i^T), and some country-specific shift parameters (E_i). To estimate equation (6) for sulfur and NO_x reductions, we need data on these measures for the European nations that participated in the Convention on Long-Range Transboundary Air Pollution. The variable definitions are listed in Table 1 and explained below. In the Appendix, the raw data are presented in Tables 1A and 2A. As noted in section 2, we have 26 countries that generate useful observations for the study. These nations are listed in the first column of Table 1A.

At the present time, there is not enough annual data to estimate the demand function for each nation, implying that we must use cross-sectional (or cross-national) data and estimate one demand function for the sample. Essentially, this approach requires that we assume, with the exception of random errors, that the demand function for each nation is identical, when controlling for measurable shift parameters. The estimated relationship must be interpreted as an "average" equation that is derived from the sample.

4.1 Variable Definitions

Measures of q_i^V and q_i^T

Emissions by country and by year are obtained from EMEP (Sandnes, 1993). For a given year, the emissions of sulfur are denoted by the variable SYY, in which the YY represents the year. For example, S80 depicts the emissions of sulfur in 1980 for the country under consideration. The NO_x emissions are denoted by NOYY, so that NO85 denotes the NO_x emissions in 1985.

The dependent variable in our models represents the voluntary reductions of sulfur or NO_x emissions. With respect to sulfur, we need a measure of voluntary contributions before and after the 30 percent reduction target, concluded at Helsinki on 8 July 1985. Because all reductions in emissions before the Helsinki Protocol are voluntary, we compute the q_i^V before the Helsinki Protocol as the difference S80 - S85 and refer to it as S80_85. After the protocol, the ratifying nations are required to reduce emissions by 30 percent of the 1980 level as soon as possible or at least by 1993. Only emission reductions in excess of the target are voluntary. Hence, to estimate demand behavior after the Helsinki Protocol, we compute voluntary reductions as $q_i^V = 0.7 \cdot S80 - S90$, which we refer to as S80_90. Our choice of 1990 as the ending year to compute the change is somewhat arbitrary; however, it is motivated by our desire to end the study period prior to the dramatic political changes in Eastern Europe and to provide some symmetry with respect to S80_85. Our qualitative conclusions are unaffected by this choice; i.e., using any ending year between 1988-1991 we generate the same qualitative conclusions.

Following the Helsinki Protocol, the target rate of reductions (q_i^T) enters the demand function as an exogenous variable. This value is referred to as TARGET and is the level of emission reductions specified in the Helsinki Protocol; i.e., 0.3•S80. We emphasize that countries with high rates of emissions in 1980 will necessarily face greater targets. As TARGET increases, we consequently expect that, ceteris paribus, voluntary contributions will decrease.

For NO_x, we present estimates based on two measures of voluntary contributions. The first is NO85_87 = NO85 - NO87, and the second is NO88_90 = NO88 - NO90. In the Appendix (Table 7A), we present the NO_x results with alternative definitions of voluntary contributions. Technically, no targets existed for NO_x during the study period, so that all changes in emissions are viewed as voluntary. Still, several nations have ratified the Sofia Protocol, making it conceivable that the demand relationship shifted in 1988. Therefore, the results presented below facilitate an explicit examination of the model before and after the Sofia Protocol. The choice of 1990 as the ending period is again somewhat arbitrary but provides consistency with the sulfur results.

Reductions in sulfur and NO_x, expressed in percentages from 1980 levels, are presented graphically in Figures 1 (for sulfur) and 2 (for NO_x). Both figures display interesting patterns in the nations' behavior with respect to emission reductions. In Figure 1, several nations, including Austria, Denmark, France, Luxembourg, the Netherlands, Spain, and Sweden, reduced emissions by more than 30 percent by 1985--before the Helsinki Protocol. Belgium, Finland, Norway, Switzerland, and West Germany achieved the 30 percent reduction very soon after 1985. Of the remaining nations, Hungary and the Soviet Union have reached the target, while Bulgaria, Czechoslovakia, East Germany, Poland and Yugoslavia have shown progress in recent years towards the target. Only Greece, Ireland (which is close to the target), Portugal,

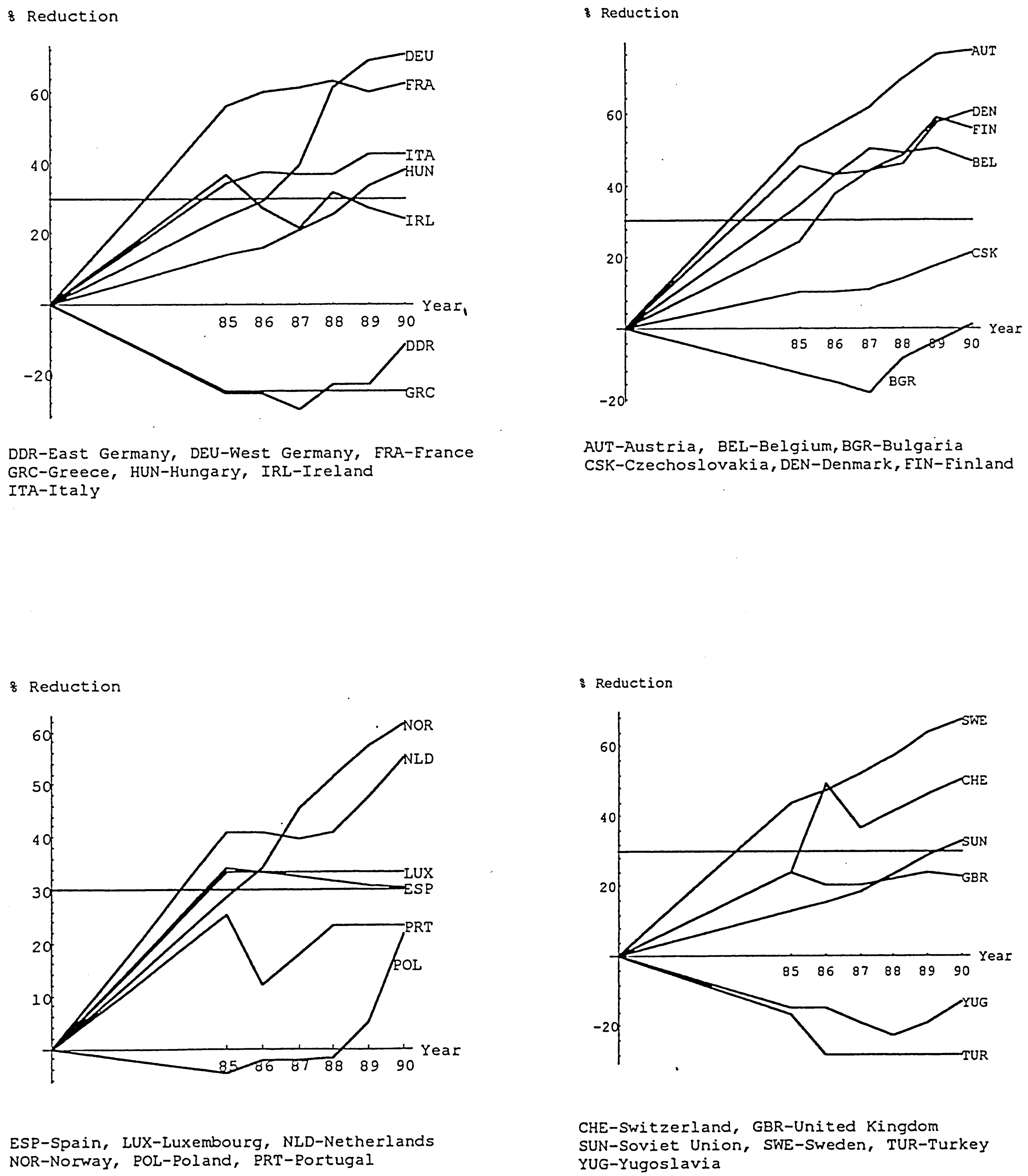

Figure 1. Percentage Reduction in Sulfur Emissions from 1980 Levels. Romania is zero for every year.

Romania (not illustrated) and the UK appear to be stationary in their rates of sulfur emissions.

In comparison to Figure 1, the patterns displayed in Figure 2 offer a stark contrast. For example, there is no clear pattern of increased reductions in emissions. Belgium, Luxembourg, Portugal, and Spain made significant reductions in the first half of the 1980s but, since then, have either decreased these reductions or have made no further progress. Alternatively, Norway, the Soviet Union, the UK, and Yugoslavia substantially increased their emissions (i.e., exhibited negative reductions) in the early 1980s and showed little evidence of reversing the trend. The remaining nations are either not showing large changes in emissions behavior or are so erratic that no pattern is evident. At a later stage, we relate this difference in behavior between sulfur and NO_x emission reductions to collective action and other considerations at the national and international level.

<u>Measures of</u> m_i

To measure a nation's income, we use the Gross National Product (GNP). This common measure of national income is not, however, without problems. Perhaps, the most difficult problem is to find cross-nationally comparable figures. This is especially true in our case because the sample of nations includes traditional market and nonmarket economies. Another problem is that there are many different sources for GNP estimates in the nonmarket economies; e.g., the Central Intelligence Agency, the World Bank, and private foundations. A third problem is that we want GNP estimates for different slices of time; thus, we need estimates that are comparable across nations and through time. Our approach is to use the estimates presented in <u>World</u>

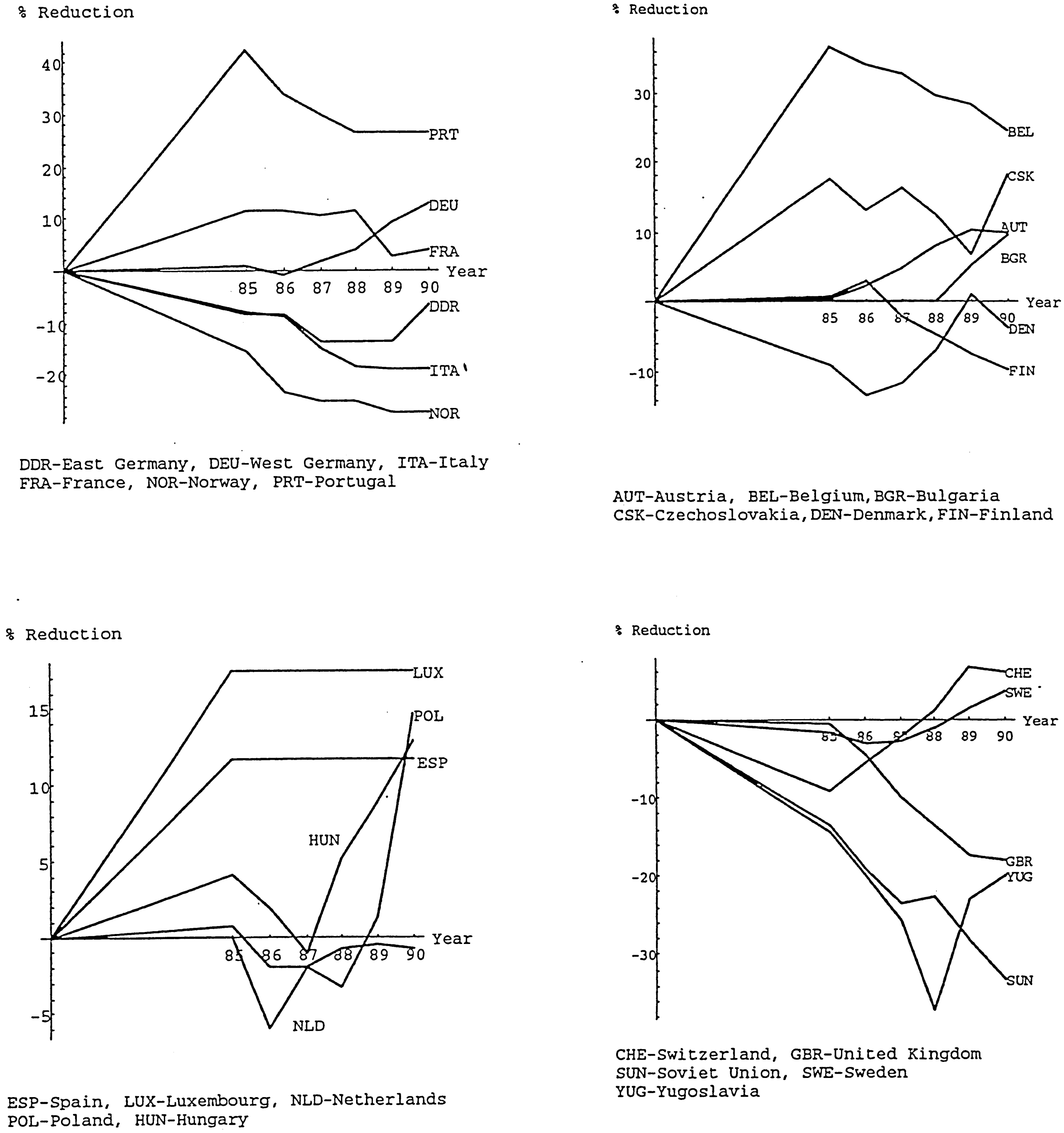

Figure 2. Percentage Reductions in NO_x Emissions from 1980 levels. Romania, Turkey, and Greece are zero for every year.

Resources: 1992-93 (World Resources Institute, 1992, Table 15.1). World Resources Institute (WRI) presents the 1989 GNP in 1989 US dollars (GNP89), providing a cross-nationally consistent measure for 1989. To generate observations for other years, we utilize the average annual growth rate (GR) of constant GNP between 1980 and 1991 available in WRI (1994, Table 15.1). For example, to compute the GNP in 1983 for country i, we compute GNP83 = $GNP89 \cdot (1 + GR)^{-6}$. The resulting estimate is expressed in 1989 US dollars.

Measures of α_{ii}

The fraction of a country's sulfur emissions that falls within its own borders (OWNSUL) is calculated from the 1985 Budget of Oxidised Sulfur in Sandnes (1993). Similarly, the fraction of NO_x emissions that falls within the country of origin (OWNNOX) is computed from Sandnes' 1985 Budget of Oxidised Nitrogen. The budgets are matrices that show, for each country, the origin of the depositions on its soil. To explain the process for calculating OWNSUL, consider the following example based on the actual data for Belgium. In 1985, Belgium's total sulfur emissions measured 226,000 tons. Of this, 66.1 percent (149,300 tons) fell within the EMEP study region. The fraction of deposition for sulfur emissions in the study area is called AREASUL; hence, for Belgium AREASUL equals .661. (For NO_x, the rate is called AREANOX.) Thus, we can identify where 149,300 tons of Belgian emissions fell by examining the EMEP's 1985 Budget of Oxidised Sulfur (see Table 3A): for example, 42,800 tons fell in Belgium itself; 23,800 tons, France; and 24,700 tons, West Germany.

To find OWNSUL, we first divide the country's deposition within its own border by the country's deposition within the study area. We then multiply by the fraction of the country's total emissions that fell within the study area.

For Belgium, this calculation is (428 ÷ 1493)•0.661 = 0.189. This procedure is equivalent to dividing the country's self-deposition by its total emissions, since (428 ÷ 2260) = 0.189. An identical procedure is used to calculate OWNNOX. OWNSUL and OWNNOX are appropriate measures for α_{ii}.

Measures of $\tilde{Q}_i$

$\tilde{Q}_i$ indicates the amount of deposition reduction provided by other nations to country i, and denotes the "spillins". As shown earlier, there are two components of spillins. The first ($\sum_{j \neq i}^{n} \alpha_{ij} q_j^V$) reflects the spillins from the voluntary reductions, and is indicated by $SPILL_i$, while the second ($\sum_{j \neq i}^{n} \alpha_{ij} q_j^T$) is a measure of the spillins from satisfying the target rate of emission reductions, and is represented by $TSPILL_i$. The computation of SPILL and TSPILL is based on EMEP's budgets for sulfur and NO_x, which in our case, the budgets are 26 by 26 matrices that show the emission sources of depositions in each country. For example, assume that the fifth row of the matrix represents the depositions in Denmark and that the second column indicates the emissions from Belgium (see Table 3A in the Appendix). Building on the earlier example for Belgium, we use the entry in the fifth row, second column in the Budget of Oxidised Sulfur, which is 1,100 tons. This means that from the 226,000 tons emitted by Belgium, 1,100 tons fell within the borders of Denmark. Thus, the empirical realization[5] of α_{52} is 1100/226000 = 0.005, which implies that when Belgium voluntarily reduces its emissions by, say, 1000 units, Denmark is expected to realize a reduction of 5 units of depositions.

Using a similar method, we can find a matrix of α_{ij}s, where $i \neq j$. With zeros along the diagonal, this matrix is the empirical realization of $\tilde{A}$

(see Table 4A in the Appendix) and it allows us to calculate the voluntary reductions in spillins for Denmark or country 5 as $SPILL_5 = \sum_{j=1}^{26} \alpha_{5j} q_j^v$, where $\alpha_{55} = 0$. Alternatively, we can represent the calculation of the 26 by 1 SPILL vector as $\tilde{A} \cdot q^v$, where q^v is the 26 by 1 vector of voluntary contributions. The calculation is similar with respect to TSPILL.

Measures of p_i

In theory, the price measure should reflect the opportunity cost of voluntarily providing a unit of q^v; i.e., the opportunity cost of reducing emissions beyond the target level. A direct measure of price is not available; hence, a proxy must be devised. For sulfur, we use a price proxy based on the fuels employed to produce energy. We hypothesize that nations with greater reliance on solid fuels (e.g., coal) find it more costly to reduce sulfur emissions. PRICESUL is computed as the fraction of total energy produced with solid fuels. Nations with large PRICESUL have relatively less reliance on nuclear and natural gas energy and, therefore, will find it more expensive to reduce sulfur emissions. For the estimates based on SO80_85, we measure PRICESUL with 1983 data, while for the other estimates, we use 1988 data.

For NO_x, we use a measure based on the number of automobiles. PRICENOX is cars per capita in 1990. Countries with more cars per capita rely relatively less on public transportation and trains and should, therefore, find it more expensive to reduce NO_x emissions. Our use of 1990 to measure PRICENOX is strictly pragmatic--it is the only year that the data are available for all countries.

Measures of E_i

E_i denotes the influences that shift a nation's emission reductions besides income, spillins, target, α_{ii}, and price. One influence, explored recently by Congleton (1992), is the extent of democracy and/or freedom in the nation. The logic of this influence is that autocracies face a higher relative price for pollution abatement than their democratic median-voter counterparts. Moreover, autocracies are less risk averse, making them less interested in policies to protect the environment. We attempt to control for this influence by using Gastil's (1989) index of civil liberties and index of political freedoms. Each index may take on an integer value from 1 through 7, with 1 being the greatest level of either civil liberties or political freedoms and 7 the least. What we refer to as GASTIL is the sum of the two indices and, therefore, it takes on integer values from 2 through 14. Ceteris paribus, countries, with higher GASTIL measures should demand less emission reductions. We use 1983 GASTIL data for the SO80_85 estimates and 1988 GASTIL data for all of the others.

A second influence that may shift the demand relationship is the potential for environmental damage caused by sulfur or NO_x emissions. For example, a country with large existing damages from acid rain may desire more sulfur emission reductions, owing to a heightened awareness of environmental problems. Similarly, a country with the potential for large damages may also demand more reductions to protect its resources. Thus, a nation with relatively large forest cover, in the case of sulfur, or a large urban population, in the case of NO_x, may desire more reductions to minimize the potential damages to their forests and exposed urban populations. To control for these influences, we examine several measures of potential damage.

We consider FOREST, which is the percentage of a nation's land area in forest and woodland. A nation with a larger percentage of forest and woodlands is susceptible to acid rain damage and, presumably, would demand more reductions in sulfur emissions. Two related measures, CONIFER and BROADL, represent the percentage of trees (conifer and broadleaf, respectively) with more than 25 percent defoliation. In contrast to FOREST, these measures reflect the actual damages due to sulfur emissions.

For potential NO_x damages, we employ two measures. The first is the percentage of the population residing in urban areas (URBAN). Because NO_x along with volatile organic compounds react with sunlight to produce tropospheric ozone, the primary damages from NO_x are to people living in urban areas. Nations with greater URBAN may, consequently, demand greater reductions in NO_x emissions. We also consider population density (POPDEN) as a measure of potential damages from NO_x.

We are particularly interested in the third set of demand shift influences, namely, international policy actions. We hypothesize that the countries that ratified the Helsinki and Sofia Protocols are more apt to have a different demand relationship when compared to the countries that did not. To investigate this hypothesis, we formed two additional shift variables: (1) HELSINKI, a binary variable that equals 1 if a country ratified the Helsinki Protocol, 0 otherwise; and (2) SOFIA, a binary variable that equals 1 if a country ratified the Sofia Protocol, 0 otherwise. While Sofia did not require a specific target rate of reductions for the time period under investigation, nor has it entered into force as of February 1991, the spirit of the protocol was to encourage reduction in NO_x. Hence, nations that ratified the Sofia Protocol may demand more NO_x emission reductions.

4.2 Econometric Model

Using the above-defined variables, we can re-specify the basic regression equation in (8) as

$$S80\_90_i = \beta_0 + \rho_1 SPILL_i + \rho_2 TSPILL_i + \beta_1 GNP_i + \beta_2 PRICESUL_i + \beta_3 OWNSUL_i + \beta_4 GASTIL_i + \beta_5 FOREST_i + \beta_6 HELSINKI_i + \gamma TARGET_i + \epsilon_i, \quad (10)$$

where S80_90 is the dependent variable and i denotes the country. In (10), the ρs, β_is, and γ are unknown slope coefficients, β_0 is a constant, and ϵ_i is an independent identically distributed random variable assumed to follow a normal distribution with a mean of 0 and a variance of σ^2. Equation (10) should be viewed as representative of our regression model; i.e., we estimate numerous similar equations by changing the dependent variable and/or the set of independent variables.

Our empirical task is to find estimates for the ρs, βs, γ, and σ^2. At first glance, it may appear that the method of ordinary least squares (OLS) is appropriate for estimating the parameters, but this is not the case. In fact, OLS would generate biased and inconsistent estimates due to the $SPILL_i$ term, which is a weighted average of q_i^v, the dependent variable. Thus, values for S80_90 appear on the left- and the right-hand side of the equation. But note that for the i^{th} observation, the SPILL term is a weighted average of the <u>other</u> (i.e., other than i) S80_90 values. Thus, the dependent variable is often said to appear in "lagged" form on the right-hand side. This terminology is lifted from time-series models where the t^{th} observation on the dependent variable is a function of the $t\text{-}1^{st}$ observation. In our case, we do not lag over time but over geographic space (i.e., countries). The SPILL term is therefore called a "spatially lagged" dependent variable (see Cressie, 1993; Anselin, 1988). Intuitively, the problem with OLS is evident by solving for the dependent variable, because the resulting expression will have the βs,

γ, and ϵ multiplied by the ρ_1 and the α_{ij}s weights, making the model nonlinear in the parameters.

To get unbiased and consistent estimates, we appeal to the method of maximum likelihood (ML), which is appropriate if the ϵ_i follow the normal distribution. Our analysis of the normal probability plot[6] of the ML residuals (see Figure 1A top in the Appendix) suggests that the normality assumption is reasonable for the models represented by equation (10). Thus, we employ the ML approach as described in Anselin (1988, Chapter 12) to estimate the parameters.

The ML parameter estimates for some alternative models of sulfur reductions are presented in Table 2, while the NO_x models are given in Table 3.[7] A quick scan of the two tables reveals that the sulfur data fit the models better than the NO_x data. In fact, approximately 65 percent of the coefficients in the sulfur models are statistically significant ($\alpha = .10$, one-tail test), while less than 23 percent are significant in the NO_x models. Despite "looking good," we still must guard against making incorrect inferences in the sulfur models. Thus, we considered three sets of regression diagnostic procedures. The procedures were performed on Model 5 presented in Table 2, because, as we argue below, it is the best model.

The first procedure involves visually examining the scatterplot of the ML residuals and normal probability plot (see Figure 1A bottom in the Appendix). Neither suggested any serious problems. The actual residuals are slightly skewed to the left, when compared to a normal distribution, and two nations (Finland and France) exhibit somewhat large residuals. Overall, however, the analysis does not suggest any serious problems with outliers or the normality assumption.

The second procedure is a test for heteroskedasticity. Using the ML residuals, the Breusch-Pagan χ^2 equals 6.3. The p-value for the test is 0.278, indicating that we fail to reject the null hypothesis of homoskedasticity. Thus, there is little reason to doubt the constant variance assumption.

Because only a fraction of the total land area in Turkey and the Soviet Union is covered under the Helsinki Protocol, we suspect that these two countries should not be treated like the others. For the third set of procedures, we re-estimated the model dropping these two nations. Because the data for CONIFER and BROADL were unavailable for these two nations, we are able to examine the effect of these additional damage measures when these countries are dropped. The results, presented in Table 5A in the Appendix, are qualitatively very similar to those presented in Table 2. Hence, there does not appear to be any evidence supporting dropping the nations from the sample.

5. EMPIRICAL RESULTS AND FORECASTS

In Table 2, the pre-Helsinki results generally confirm the model of voluntary behavior that underlies our empirical specification. The negative and significant estimate on the SPILL term is entirely consistent with strategic (within-region) free riding associated with the Nash assumption, whereas the positive income effect is consistent with the demand for emission reductions being income normal. The GASTIL and OWNSUL measures perform as expected, but the OWNSUL parameter estimates are marginally significant in Model 2. In the case of GASTIL, political and civil freedoms (low GASTIL) apparently lead to greater environmental concern and larger emission reductions. Neither PRICESUL nor FOREST is significant, probably because they imprecisely measure the true price and potential damage effects.

For the post-Helsinki result, our theoretical characterization is also supported. The coefficients on the SPILL, GNP, GASTIL as well as the additional terms, TARGET and HELSINKI, have the anticipated sign and are significant. OWNSUL has the correct sign and is marginally significant in Model 5. As before, PRICESUL and FOREST are insignificant in the post-Helsinki estimates. Statistically, Model 5 outperforms both Model 3 and 4. The respective χ^2 values for comparing the likelihood functions are 17.90 and 3.70, indicating that Model 5 is unquestionably better than Model 3 and somewhat better than Model 4 at a confidence level of approximately 94 percent. Model 5 also provides more precise estimates of OWNSUL and GASTIL when compared with Model 4; hence, we view Model 5 as the best representation for the data.

Ceteris paribus, nations that faced a greater target level of reductions are achieving less in voluntary reductions. In addition, nations that ratified the Helsinki Protocol appear more willing than nonratifiers to make reductions beyond the targetted level. When comparing the pre-Helsinki to the post-Helsinki estimates, we find that the size of the spillin response and the income effect increased quite substantially in the post-Helsinki sample. The emission reductions beyond the mandated 30 percent cut are subjected to greater strategic behavior than the initial pre-Helsinki cuts. The increased income effect suggests that the post-Helsinki reductions are more discretionary, perhaps owing to the lack of a political constraint that mandates additional cuts.

In Table 3, the NO_x results offer much less support for our voluntary reduction model. The SPILL terms are still negative and of even greater magnitude. The income parameters are negative and significant in the pre-Sofia period, while they are negative and marginally significant in the post-

Sofia period. Although we did not expect the negative signs on the GNP term, they probably reflect the fact that the primary source of NO_x emissions--automobiles and trucks--has a procyclical activity pattern. As GNP increases, there are necessarily more traffic flows and more emissions. To the extent that the variation in cross-national GNP is related to differences in the business cycle, we should expect a negative association with emission reductions. In both periods, the remaining parameters are generally insignificant. Although its sign is unexpected, the GASTIL parameter approaches significance in the post-Sofia period. POPDEN and URBAN, our proxy variables for damages, once again, do not perform as predicted. Based on the likelihood function values, the parsimonious models 1 and 4 must be maintained as the best representation of the data.

By contrasting the sulfur and NO_x results, we gain several interesting insights. First, at the supranational level we see evidence of strategic behavior for both environmental problems. This lends support to our modeling efforts that cast each problem as a regional collective action problem. Second, the influence of political and civil liberties affects the two pollutants differently: liberties are supportive of emission reductions for sulfur, but are marginally nonsupportive for NO_x. This difference can be traceable to collective action considerations at the national level. In the case of sulfur, the major share of emissions stems from power plants that are government-controlled monopolies; in the case of NO_x, the major share of emissions come from a large number of small (mobile) polluters. For NO_x, emission control requires a national program aimed at a large number of small emitters who burn a variety of fuels. Unless a program is applied simultaneously to all groups, one group of emitters may free ride on the efforts of the others; hence, a collective action problem exists at the national level. The GASTIL results suggest that freedoms enhance the ability of a nation to respond to its constituency and to coordinate efforts at the national level when emissions are concentrated. These same freedoms hinder the control of efforts at the individual level when emissions are diverse as citizens resist control either through free riding or organized lobbying activities. Third, we see that the amount of a nation's emissions that fall within its borders (OWNSUL and OWNNOX) is much more relevant in the sulfur model. This contrast reflects the nature of the two problems. For sulfur, a relatively large fraction of a nation's emission falls on itself, while for NO_x, the emissions travel much further or dissipate into the atmosphere. On average, a smaller percentage of a nation's NO_x emissions falls within the study area. The transferability of NO_x means a greater role for strategic behavior at the supranational level, which is borne out by the larger absolute coefficients on the SPILL variable when the two pollutants are compared. Finally, the treaty's effects are quite different. Helsinki is a significant deterrent in the post-Helsinki period, because it had entered into force in September 1987 during the period under investigation, which goes through 1990. Since the Sofia Protocol did not enter into force until February 1991, we really do not have a post-Sofia period to ascertain the impact of the treaty.

The parameter estimates presented in Tables 2 and 3 facilitate forecasts of voluntary sulfur and NO_x emissions reductions. Using Model 5 in Table 2, Model 4 in Table 3, 1992 GNP, and 1992 GASTIL values (McColm et al.1993), we calculate forecasts for 1992 emission reductions and present the findings in Table 4. The predicted values for sulfur reductions are labeled S80_92P, while the predicted reductions for NO_x are labeled NO88_92P. The forecasts assume that PRICESUL, PRICENOX, OWNSUL, OWNNOX and SPILL remain constant. For comparison, the actual voluntary emission reductions in 1992 are also presented in Table 4. Forecasts are not presented for East and West Germany, the Soviet Union, and Yugoslavia, owing to changes in these nations during and after 1990.

The forecasts provide additional information about the validity of our models. Turning first to the sulfur forecasts, we see reasonable predictions for Austria, Belgium, the Netherlands, Portugal, Romania, and Sweden. However, incorrect signs characterize the forecasts for Greece, Ireland, Spain, and Turkey. The remaining forecasts, while not very accurate, are not of unexpected quality for a cross-sectional model. Similar conclusions follow an analysis of the NO_x forecasts. Reasonably accurate forecasts appear for Austria, Denmark, Hungary, Italy, the Netherlands, Spain, Sweden, and Switzerland, while the model predicts the wrong sign for Belgium, Finland, Ireland, and Norway. In general, the forecast exercise provides little evidence for discarding our econometric models.

6. POLICY IMPLICATIONS

Although both the Helsinki and Sofia Protocols are extensions to the same LRTAP Convention, the empirical results indicate, on average, vastly different behavior in regards to the curtailment of sulfur and NO_x pollution. At first, this seems surprising because the same set of nations is involved and both pollutants result in environmental damage. An understanding of the differences between these two problems may assist policy makers in designing treaty provisions and procedures for other pollution problems.

In Figure 1, presented earlier, a majority of nations had either met or exceeded the 30 percent reductions (from 1980 levels) in sulfur emissions by the end of 1985--the year that the Helsinki Protocol was signed. Other nations (e.g., Switzerland and West Germany) were near to the stipulated reduction in 1985. This suggests that, once a majority of nations can meet a given standard of reductions, the treaty is drafted and subsequently approved as others catch up. For many participants, the cutbacks achieved served as a blueprint for the treaty stipulations. A similar kind of pattern regarding the Sofia Protocol emerges in the case of NO_x from Figure 2. Since the reductions were slow to achieve and modest, the stipulated reductions in the Sofia Protocol were also modest--maintaining 1987 emission levels. In 1988, eight nations had reduced NO_x emissions below those of 1987. Another five had reduced NO_x emissions by 1990 prior to the treaty being ratified. Once again, actions preceded the drafting and ratifying of the treaty on the behalf of many participants.

If this pattern of voluntary reductions preceding the framing of treaties continues, then a policy prediction follows from Table 4. In the case of sulfur, the percent of voluntary sulfur emission reduction (%S) achieved in 1992 is on average 4.7 percent <u>beyond</u> the targetted reductions of the Helsinki Protocol. In Table 4, ten nations have achieved voluntary reductions greater than 15 percent <u>beyond</u> the 30 percent target (see the %S column). Based on this pattern, we would predict that a new, stronger protocol will emerge in the next couple of years that restricts sulfur emissions by another 10-15 percent from 1980 levels. In the case of NO_x, we can be much less sanguine. Reductions from 1987 levels are 1.7 percent (on average) for the 22 sample nations in Table 4. Nations have until the end of 1994 to return to 1987 levels. Subsequent protocols on NO_x will take a long time to achieve. Uncertainty regarding the harmful effects of NO_x may add to the reluctance of nations to rush into a treaty that restricts pollutants. The detrimental effects of sulfur-induced acid rain on forest degradation appear better understood than those of nitrogen-induced degradation (Economic Commission for Europe, 1992, p. 48). Poterba (1993) makes a strong case that the Montreal Protocol on ozone moved forward in terms of its mandated cutbacks once much of the uncertainty regarding the harmful effects of ozone shield depletion was resolved. Analogously, uncertainty regarding their harm and a difficulty in monitoring may have been behind the slowness to conclude a protocol on curbing volatile organic compounds (VOCs). Scientific expenditures on research for monitoring and evaluating pollutants may be a major factor behind the framing and ratification of environmental treaties.

In section 5, a number of important factors distinguished the collective action nature of the sulfur problem from that of NO_x. For instance, a greater fraction of NO_x can be transferred outside the treaty region, thus leading to greater free riding in terms of emission reductions. This suggests the need for a larger treaty region if the externality is to be truly internalized. As a consequence, monitoring and evaluation activities need to be extended beyond their current region. A similar recommendation does not follow for sulfur. A second factor concerns the share of a country's pollutant that befouls its own soil. This share is larger for sulfur than for NO_x. Understandably, a nation is more concerned about doing something about its sulfur emissions than its NO_x emissions. Transnational liability assignments and a system of enforcement may be necessary if nations are to become more responsible about NO_x as a pollutant. These are not easy changes to engineer for transnational relationships that hinge, to a large extent, on national autonomy.

A third policy consideration involves control at the national level. For NO_x, nations must achieve greater control over mobile polluters. If increased demands for a cleaner environment are to be attained as a nation's income rises, then, in the case of NO_x individual freedoms have to be traded off for more centralized control over the polluters. These controls may have to be intensified as income grows owing to the pro-cyclical nature of the pollutant. For NO_x unlike sulfur, policy must first be directed at fixing the collective action problem at the national level. Then attention can be focused on the second tier, where collective action is needed at the supranational level. If the first tier problem is not resolved, there will be little progress on the second.

A fourth consideration concerns inducements or selective incentives for some nations. The pattern of emissions and their reductions differ greatly among the convention members, due to differing technologies and incentives (i.e., OWNSUL and OWNNOX). For example, the transitional economies have a difficult time cutting their sulfur emissions when compared with the other protocol members. For the most part, treaties view signers identically despite great differences in emissions and technology; mandated cuts apply in equal percentage terms to all. A degree of differentiation that changes over time may be supportive of treaty ratification. Because these transitional nations tend to do more for curbing NO_x, a trade-off among pollutants might facilitate treaty ratification and compliance in the short-run.

Fifth, nations that are first able to achieve pollution reductions may need to assist and advise others. The development of new technologies to curb sulfur and NO_x may best be developed collectively.

7. CONCLUDING REMARKS

In this paper, we formulate a voluntary contributions model to explain the cutbacks in sulfur and NO_x emissions in the 1980s. This model assumes that the collective action problem has been solved at the national level by depicting the decision maker as a unitary actor that has its constituency's wishes at heart. At the transnational level, strategic behavior is allowed as nations rely on the emission reductions of others to substitute for their own efforts--i.e., free riding is permitted. The model is used to derive an econometric specification that is applied cross-sectionally to analyze sulfur and NO_x reductions before and after protocols to the LRTAP Convention.

Two different experiences emerge when the econometric model is applied. For sulfur reductions, the model and its forecasts perform reasonably well, thus supporting our theoretical construct. Free riding does, indeed, characterize the ratifiers of the Helsinki Protocol. Increases in income and political freedoms augment emission reductions. This suggests that foreign aid and the promotion of democracy on behalf of the wealthier countries can have a dividend in terms of a better environment for all. Greater target levels limit the extent of voluntary reductions in the post-Helsinki era. These cutbacks are marginally related to the extent that a country's pollution is deposited on its own territory. The forecasts bode well for greater mandated reductions being placed into future protocols.

For NO_x, the model performs in a much less convincing manner. This is probably due to the large number of small polluters whose uncoordinated actions call into question our unitary decision maker assumption at the national level. In fact, political freedoms appear to undermine the nations' actions to curb NO_x pollutants, thus lending support to this hypothesis. NO_x emissions increased with national income. A collective action problem exists at the national and transnational level. Most significantly, policy recommendations are not necessarily the same for sulfur and NO_x owing to the adverse influence of increased income and augmented freedoms. Thus, we see that two collective action problems that have some similarities do not require the same policy prescriptions. This is an important insight. For NO_x, greater control needs to be instituted at the national level, prior to the framing of tougher treaties. In hindsight, the LRTAP Convention was properly designed when it provided for protocols to focus on separate pollutants. If all pollutants had been treated the same, much less progress would have been made for sulfur.

FOOTNOTES

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1. See UN Environment Programme (1991) for treaty and protocol text.

2. Our earlier work on sulfur did not distinguish between the voluntary and targetted cutbacks. Nor did it examine NO_x. Many other differences between the two studies exist (see Murdoch and Sandler, 1994b).

3. See Eliassen and Saltbones (1983) for a discussion of the model behind the construction of these matrices.

4. On Nash subscription models for impure public goods, see Cornes and Sandler (1986, Chapter 7) and McGuire (1990).

5. This ratio can also be computed by multiplying (1100/149300) by (149300/226000). The first ratio indicates the fraction of Belgium's within-region depositions delivered to Denmark, while the second ratio is the fraction of Belgium's emissions that fell within the study area.

6. The normal probability plot is also called the normal Q-Q plot. See, Cleveland (1993, Chapter 2).

7. The parameter on $TSPILL_i$ (ρ_2) is insignificant in all models (see Table 6A in the Appendix). Thus, we have dropped this variable when presenting the main results.

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Table 1. Variable Names, Descriptions, and Sources

Variable	Description and Source
S80_85	Voluntary reductions in sulfur (S) emissions from 1980 to 1985, calculated as the difference between 1980 and 1985 emissions. Positive values indicate that sulfur emissions fell in this period, so that the nation contributed positively to environmental quality. Source: Sandnes (1993). Units: 1000 tons.
S80_90	Voluntary reductions in sulfur emissions from 1980 to 1990, calculated as the difference between 70% of 1980 emissions and the 1990 emissions. Positive values indicate that the nation reduced emissions more than the target rate of 30% of 1980 emissions. Reductions beyond the target rate are considered voluntary. Source: Sandnes (1993). Units: 1000 tons.
NO85_87	Voluntary reductions in NO_x emissions from 1985 to 1987, calculated as the difference between 1985 and 1987 emissions. Positive values indicate that NO_x emissions fell in this period. Source: Sandnes (1993). Units: 1000 tons.
NO88_90	Voluntary reductions in NO_x emissions from 1988 to 1990, calculated as the difference between 1988 and 1990 emissions. Source: Sandnes (1993). Units: 1000 tons.
GNP	Gross National Product for various years, calculated from the 1989 GNP and the 1980-91 average annual growth rate in real GNP. Source: World Resources Institute (1992, 1994). Units: 10 million 1989 $US.
OWNSUL	The fraction of a country's sulfur emissions that fell within that country's borders. This measure is an empirical representation for α_{ii}. Source: Computed from Sandnes (1993).
OWNNOX	The fraction of a country's sulfur emissions that fell within that country's borders. Source: Computed from Sandnes (1993).
AREASUL	The fraction of a country's sulfur emissions deposited on one of the 26 countries in our study. Source: Computed from Sandnes (1993).
AREANOX	The fraction of a country's NO_x emissions deposited on one of the 26 countries in our study. Source: Computed from Sandnes (1993).
SPILL	The reduction in emissions (either S or NO_x) owing to reduced emissions in the other 25 sample nations. The calculations are described in the text and use data from Sandnes (1993). SPILL depends on the measure of emission reductions, so that for each measure there is a corresponding SPILL term. Units: 1000 tons.

Table 1. (cont.)

PRICESUL	The price of reducing a unit of S emissions, calculated as the fraction of total energy produced with solid fuels. An estimate for 1983 is calculated as the average of the 1979-80 and 1987-88 values. Source: United Nations (1981, 1990).
PRICENOX	The price of reducing a unit of NO_x emissions, calculated as the number of automobiles per capita in 1990. Source: UNEP (1993) for automobiles and World Resources Institute (1992) for population. Units: Automobiles per 1000 people.
GASTIL	The sum of Gastil's index of civil liberties and political freedoms, where $2 \leq \text{GASTIL} \leq 14$. Source: Gastil (1989, 1991).
FOREST	Percentage of a nation's land area classified as forest and woodland. Source: UNEP (1993).
URBAN	Percentage of the population living in urban areas in 1990. Source: World Resources Institute (1992).
POPDEN	Population per square hectare. An estimate for the 1985 value is calculated using the 1979-89 average annual population growth rate and the 1990 population estimates. Source: World Resources Institute (1992). Units: 1000 people per square hectare.
TARGET	The target rate of S emission reductions set by the Helsinki Protocol. This rate is 30% of the 1980 emissions. Units: 1000 tons.
HELSINKI	A binary variable equal to 1 if a nation ratified the Helsinki Protocol and 0 otherwise. Source: Personal correspondence with the Treaty Section, Office of Legal Affairs, United Nations.
SOFIA	A binary variable equal to 1 if a nation ratified the Sofia Protocol and 0 otherwise. Source: Personal correspondence with the Treaty Section, Office of Legal Affairs, United Nations.

Table 2. Maximum Likelihood Estimtes of the Sulfur Emission Reduction Regressions. Asymptotic t-ratios in Parentheses.

Variables	Pre-Helsinki (1)	Pre-Helsinki (2)	Post-Helsinki (3)	Post-Helsinki (4)	Post-Helsinki (5)	Post-Helsinki (6)
SPILL	-0.776 (-4.53)	-0.791 (-4.77)	-2.639 (-9.83)	-3.15 (-16.75)	-3.879 (-20.54)	-4.011 (-22.54)
GNP	4.077 (4.08)	3.646 (3.37)	1.385 (1.58)	6.233 (4.52)	5.27 (3.92)	4.78 (3.49)
PRICESUL	59.784 (0.46)	59.521 (0.47)	-13.424 (-0.10)	64.235 (0.60)	135.715 (1.29)	171.21 (1.61)
OWNSUL	1109.988 (1.46)	1628.21 (1.77)	592.239 (0.83)	586.561 (1.06)	889.546 (1.66)	1493.629 (2.03)
GASTIL	-33.877 (-3.06)	-35.769 (-3.24)	-46.796 (-3.99)	-24.248 (-2.25)	-32.94 (-3.12)	-36.906 (-3.44)
TARGET				-0.83 (-4.10)	-0.758 (-3.98)	-0.767 (-4.13)
HELSINKI					122.583 (2.06)	162.892 (2.44)
FOREST		-2.625 (-0.96)				-2.578 (-1.17)
CONSTANT	-51.905 (-0.33)	-82.375 (-0.52)	44.535 (0.30)	-12.508 (-0.11)	-141.763 (-1.10)	-219.501 (-1.54)
-Log Likelihood	149.477	149.021	149.155	142.725	140.879	140.213

Note: The pre-Helsinki models use the 1983 data for GNP, PRICESUL, GASTIL, and FOREST. The post-Helsinki models use the 1988 data.

Table 3. Maximum Likelihood Estimates of the NO_x Emission Reduction Regressions. Asymptotic t-ratios in Parentheses.

Variables	Dependent Variable = NO85_87			Dependent Variable = NO88_90					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SPILL	-6.334 (-13.65)	-6.647 -(13.34)	-6.537 (-14.72)	-9.097 (-9.84)	-8.105 (-10.15)	-9.156 (-9.73)	-9.037 (-9.45)	-8.049 (-9.78)	-9.096 (-9.35)
GNP	-1.383 (-7.60)	-1.422 (-7.84)	-1.387 (-7.72)	-0.44 (-1.41)	-0.549 (-1.76)	-0.436 (-1.40)	-0.445 (-1.43)	-0.554 (-1.78)	-0.441 (-1.42)
PRICENOX	0.101 (1.12)	0.084 (0.93)	0.136 (1.35)	0.034 (0.21)	-0.002 (-0.01)	0.055 (0.29)	0.103 (0.45)	0.064 (0.28)	0.124 (0.51)
OWNNOX	312.322 (0.99)	456.33 (1.31)	272.622 (0.87)	242.778 (0.41)	522.424 (0.79)	225.4 (0.38)	270.805 (0.45)	547.311 (0.83)	253.373 (0.42)
GASTIL	0.784 (0.27)	1.226 (0.43)	1.128 (0.39)	7.308 (1.29)	7.489 (1.33)	7.625 (1.32)	9.117 (1.29)	9.235 (1.31)	9.437 (1.32)
POPDEN		9387.06 (0.96)			18255.7 (0.99)			18115.2 (0.98)	
URBAN			-0.501 (-0.75)			-0.293 (-0.23)			-0.294 (-0.23)
SOFIA							-21.255 (-0.43)	-20.56 (-0.42)	-21.267 (-0.43)
CONSTANT	-51.352 (-1.17)	-64.743 (-1.43)	-28.663 (-0.55)	-8.166 (-0.11)	-29.3 (-0.37)	4.558 (0.05)	-26.622 (-0.30)	-46.986 (-0.52)	-13.855 (-0.13)
-Log Likelihood	112.279	111.828	111.998	129.317	128.879	129.290	129.224	128.791	129.198

Note: All models use the 1988 values for GNP and GASTIL.

Table 4. Predicted, Actual, and Percentage Changes for Voluntary Emission Reductions of Sulfur and NO_x in 1992.

	Sulfur			NO_x		
Country	S80_92P	S80_92	%S	NO88_92P	NO88_92	%N
Austria	91.9	97.3	48.9	18.0	10.0	7.7
Belgium	89.2	65.8	15.9	14.0	-23.0	-12.8
Bulgaria	-53.8	-112.5	-11.0	25.4	142.0	34.4
Czechoslovakia	-61.4	-14.3	-0.9	17.9	164.0	11.7
Denmark	10.0	36.2	16.0	15.7	9.0	7.2
Finland	172.8	107.4	36.8	15.9	-23.0	-10.7
France	223.6	483.3	29.0	-17.1	-195.0	-11.0
Greece	2.3	-110.0	-55.0	27.7	0.0	0.0
Hungary	3.0	66.2	8.1	19.6	21.0	13.8
Ireland	11.9	-17.3	-15.6	18.3	-8.0	-13.0
Italy	148.5	240.0	12.6	-29.0	-6.0	-3.6
Luxembourg	59.0	0.4	3.3	24.1	0.0	0.0
Netherlands	65.5	62.1	26.7	20.1	4.0	2.0
Norway	101.5	25.0	35.7	41.8	-1.0	-0.4
Poland	-294.4	-63.0	-3.1	17.2	345.0	21.2
Portugal	-1.3	-8.9	-6.7	16.4	0.0	-5.2
Romania	-239.9	-270.0	-30.0	58.2	0.0	0.0
Spain	-111.9	4.0	0.2	2.5	0.0	0.0
Sweden	129.0	97.0	37.3	1.4	19.0	6.2
Switzerland	186.9	13.1	20.8	27.2	19.0	12.5
Turkey	40.2	-80.4	-58.3	29.0	0.0	0.0
UK	-100.7	-172.7	-7.1	-16.4	-103.0	-7.2
Mean	21.4	20.4	4.7	15.8	17.0	1.7

Notes: Forecasts for East and West Germany, the Soviet Union, and Yugoslavia are not presented because the data for 1992 are incompatible with the sample period.

S80_92P--The predicted voluntary reduction in sulfur emissions in 1992.

S80_92--The actual voluntary reduction in sulfur emissions in 1992.

%S--The percentage reduction in voluntary sulfur emissions using 1980 as the base year.

NO88_92P--The predicted voluntary reduction in NO_x emissions in 1992.

NO88_92--The actual voluntary reduction in NO_x emissions in 1992.

%N--The percentage reduction in voluntary NO_x emissions using 1987 as the base year.

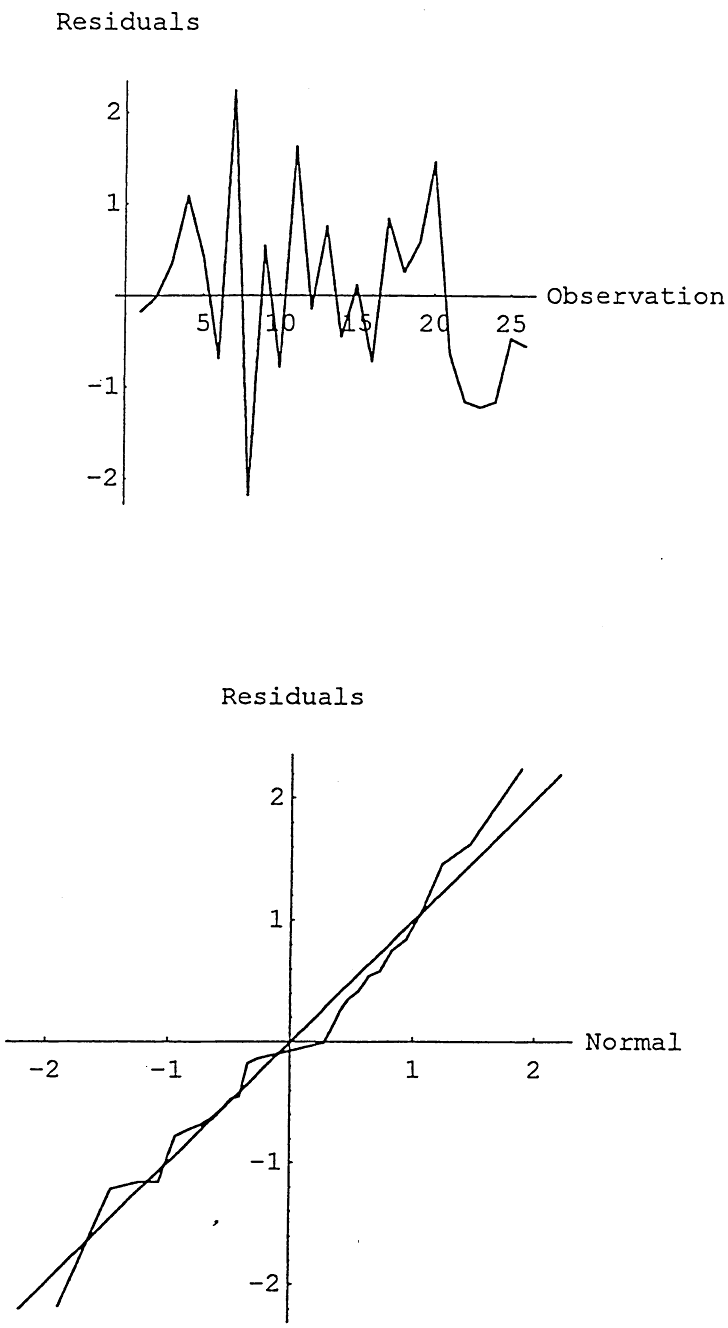

Figure 1A. (Top) Plot of Standardized Residuals. (Bottom) Normal Probability Plot of the Standardized Residuals. Based on the residuals from model (5) in Table 2.

APPENDIX TABLES

Table 1A. Reduction in Emissions and SPILL Measures. Raw Data.

Country	Code	S80_85	S80_90	NO80_90	NO85_90	NO85_87	NO88_90	SPILL S80_85	SPILL S80_90	SPILL NO80_90	SPILL NO85_90	SPILL NO85_87	SPILL NO88_90
Austria	AUT	101	94.3	24	23	11	4	38.362	7.619	10.356	2.916	-4.305	8.140
Belgium	BEL	188	67.8	108	-53	-16	-22	25.701	14.843	3.338	-0.316	-1.901	0.927
Bulgaria	BGR	-132	-292.5	40	40	0	39	4.047	-17.253	-1.033	-0.425	-2.343	2.846
Czechoslovakia	CSK	160	-136.3	217	5	-16	67	9.071	-27.71	14.817	13.873	-5.662	18.252
Denmark	DNK	54	68.2	-10	15	-7	9	8.544	1.846	0.619	-0.347	-1.710	1.424
Finland	FIN	101	74.4	-26	-28	-8	-14	19.494	4.746	-11.504	-6.057	-5.909	-0.723
France	FRA	934	538.3	73	-135	-15	-135	91.900	22.469	16.993	-2.964	-12.212	11.631
E. Germany	DDR	-550	-895	-40	10	-30	40	47.942	29.775	27.003	12.565	-2.89	14.997
W. Germany	DEU	399	647.9	380	359	32	259	93.821	-11.206	8.661	-23.934	-14.595	-5.588
Greece	GRC	-50	-110	0	0	0	0	3.046	-9.875	0.097	0.155	-1.475	2.16
Hungary	HUN	114	66.2	35	24	-14	21	10.433	-17.263	4.665	1.701	-3.433	7.521
Ireland	IRL	41	-6.3	-62	-44	-24	-13	6.982	0.063	-2.133	-2.818	-1.756	-0.525
Italy	ITA	648	240	-281	-166	-105	-6	37.404	4.359	11.637	3.206	-2.730	6.146
Luxembourg	LUX	4	0.4	4	0	0	0	2.016	1.176	0.512	-0.034	-0.082	0.011
Netherlands	NLD	95	59.1	-4	-8	-15	0	31.242	17.996	9.879	0.976	-2.734	3.542
Norway	NOR	20	22	-50	-22	-18	-4	22.509	6.294	-4.56	-4.201	-4.762	0.709
Poland	POL	-100	-170	220	220	-30	270	16.367	-56.009	18.898	4.896	-9.044	14.799
Portugal	PRT	34	-8.9	44	-26	-20	0	6.516	0.672	1.128	-0.150	-0.105	-0.045
Romania	ROM	0	-270	0	0	0	0	18.089	-21.787	0.25	1.057	-8.637	11.662
Spain	ESP	565	4	111	0	0	0	31.055	11.377	6.401	-6.074	-4.039	-1.348
Sweden	SWE	114	97	15	22	-5	19	30.833	9.538	-7.302	-4.795	-7.736	2.755
Switzerland	CHE	15	13.1	12	30	14	10	29.691	14.083	0.165	-2.872	-2.384	-0.085
Turkey	TUR	-23	-80.4	0	0	0	0	3.991	-17.403	-1.667	-0.790	-2.820	2.420
Soviet Union	SUN	813	194.4	-1057	-627	-318	-334	63.606	-76.888	59.341	41.079	-20.827	67.156
UK	GBR	587	-172.7	-417	-402	-217	-103	25.041	11.088	3.648	-1.855	-3.018	0.966
Yugoslovia	YUG	-97	-282.6	-70	-20	-40	60	51.808	0.572	5.639	0.725	-7.498	9.352

Note: See Sources and units in Table 1. NO80_90 indicates voluntary reductions in NO_x from 1980 to 1990, calculated as the difference between 1980 NO_x and 1990 emissions. NO85_90 indicates voluntary reductions in NO_x from 1985 to 1990, calculated as the difference between 1985 NO_x and 1990 emissions.

Table 2A. Additional Raw Data.

Code	GNP89	GR	OWN SUL	OWN NOX	AREA SUL	AREA NOX	PRICE SUL	PRICE NOX	GAS-TIL	FOR-EST	CON-IFER	BROADL	URBAN	POP DEN	TAR-GET	HEL-SINKI	SOFIA
AUT	12.28	0.023	0.229	0.030	0.496	0.220	0.092	487.071	2	39	12	16.6	58.4	0.001	59.7	1	1
BEL	16.923	0.022	0.189	0.009	0.661	0.212	0.391	432.487	2	21	10.8	10	96.9	0.003	124.2	1	0
BGR	2.158	0.017	0.189	0.002	0.262	0.008	0.956	146.171	14	35	7.6	8.8	67.7	0.001	307.5	1	1
CSK	12.493	0.007	0.258	0.015	0.645	0.110	0.927	213.274	13	37	27	29.1	77.5	0.001	465.3	1	1
DNK	10.995	0.022	0.117	0.013	0.460	0.259	0	368.288	2	12	21	14	87.0	0.001	67.8	1	1
FIN	11.616	0.029	0.296	0.045	0.569	0.184	0.327	448.394	3	76	17	7.9	59.7	0	87.6	1	1
FRA	104.744	0.023	0.334	0.099	0.600	0.310	0.199	503.919	3	27	9.1	5.3	74.3	0.001	500.7	1	1
DDR	16.692	0.023	0.247	0.004	0.676	0.040	0.957	317.169	13	28	15.5	9	87.4	0.002	645	1	1
DEU	133.219	0.023	0.300	0.073	0.667	0.387	0.697	522.978	3	30	14	16.5	77.2	0.003	479.1	1	1
GRC	5.536	0.016	0.142	0.045	0.243	0.166	0.845	251.045	4	20	7.7	28.5	62.5	0.001	60.0	0	0
HUN	2.735	0.005	0.260	0.008	0.702	0.064	0.365	208.057	9	18	9.4	7	61.3	0.001	244.8	1	1
IRL	3.151	0.024	0.203	0.016	0.379	0.119	0.360	280.376	2	5	4.8	0	57.1	0.001	33.3	0	0
ITA	91.431	0.024	0.257	0.043	0.399	0.118	0.013	520.978	2	23	13.8	2.9	68.9	0.002	570	1	1
LUX	0.979	0.020	0.163	0	0.725	0.400	0	527.027	2	10	11.1	12.3	84.2	0.001	3.6	1	1
NLD	24.749	0.021	0.146	0.033	0.549	0.633	0	403.211	2	9	14.5	25.4	88.5	0.004	69.9	1	1
NOR	7.567	0.025	0.226	0.106	0.384	0.362	0.002	461.520	2	27	20.8	18.2	75.0	0	21.0	1	1
POL	6.859	0.012	0.312	0.021	0.662	0.114	0.966	166.502	10	29	24.2	7.1	61.8	0.001	615	0	0
PRT	4.692	0.032	0.210	0.019	0.337	0.067	0.160	213.605	3	32	1.7	0.8	33.6	0.001	39.9	0	0
ROM	8.028	0.003	0.330	0.016	0.579	0.056	0.324	60.034	14	28	6.9	10.4	52.7	0.001	270	0	0
ESP	38.165	0.032	0.250	0.028	0.315	0.050	0.559	366.777	3	31	7.3	6.8	78.4	0.001	498	0	0
SWE	19.167	0.020	0.295	0.113	0.527	0.416	0	465.047	2	68	12.3	5.2	84.0	0	78.0	1	1
CHE	20.679	0.022	0.238	0.048	0.452	0.313	0	498.790	2	26	15	7	59.9	0.002	18.9	1	1
TUR	8.239	0.050	0.275	0.042	0.327	0.066	0.701	42.241	6	26	-9	-9	61.3	0.001	41.4	0	0
SUN	276.694	0.020	0.493	0.061	0.543	0.072	0.218	243.711	11	42	-9	-9	65.8	0	1869.	1	1
GBR	88.153	0.028	0.256	0.027	0.453	0.141	0.289	408.683	2	10	27	20	89.1	0.002	734.7	0	1
YUG	5.826	-0.007	0.324	0.018	0.570	0.063	0.657	193.196	10	37	17.5	9	56.1	0.001	195.6	0	1

Note: -9 indicates missing values. GR denotes annual average real GNP growth for 1980-91.

Table 3A. Budget of Oxidised Sulfur, 1985. Hundreds of Tons.

	AUT	BEL	BGR	CSK	DNK	FIN	FRA	DDR	DEU	GRC	HUN	IRL	ITA	LUX	NLD	NOR	POL	PRT	ROM	ESP	SWE	CHE	TUR	SUN	GBR	YUG
AUT	224	39	5	295	6	1	119	414	281	2	84	2	198	3	16	0	153	0	21	12	2	14	0	13	102	105
BEL	0	428	0	18	3	0	113	61	155	0	1	2	2	2	35	0	15	0	1	7	1	0	0	3	126	1
BGR	4	3	2189	72	2	1	7	94	23	21	103	0	36	0	2	0	82	0	324	3	1	0	7	91	14	163
CSK	41	33	12	3582	16	2	70	1439	303	1	419	2	54	2	18	1	788	0	80	11	5	3	0	66	118	94
DNK	0	11	1	23	202	2	13	107	72	0	4	2	1	0	11	4	34	0	2	2	14	0	0	11	97	1
FIN	1	7	1	47	23	565	9	146	48	0	8	1	1	0	6	8	142	0	4	1	64	0	0	704	60	2
FRA	10	238	3	190	20	2	2452	549	607	1	33	15	288	12	73	1	161	14	17	331	6	20	0	28	616	43
DDR	5	51	3	563	36	2	76	6682	521	0	25	3	8	2	34	1	281	0	11	12	7	1	0	27	154	10
DEU	21	247	3	417	52	2	480	1632	3598	1	33	11	83	13	144	2	282	2	13	50	9	22	0	33	569	31
GRC	3	3	189	45	2	0	9	56	18	356	52	0	47	0	2	0	51	0	88	4	1	0	15	41	16	70
HUN	29	10	17	316	5	1	26	263	76	3	1824	1	81	0	5	0	225	0	150	4	2	1	1	51	37	256
IRL	0	6	0	5	1	0	11	21	18	0	1	142	1	0	3	0	6	0	0	2	0	0	0	2	141	0
ITA	30	27	17	219	7	1	197	356	183	19	111	2	3216	2	12	0	183	2	25	44	3	29	4	28	93	216
LUX	0	3	0	2	0	0	10	5	10	0	0	0	0	13	1	0	1	0	0	1	0	0	0	0	4	0
NLD	0	94	0	24	5	0	64	97	291	0	2	3	2	0	201	0	19	0	1	7	1	0	0	4	204	1
NOR	1	17	0	35	37	25	23	128	77	0	12	7	1	0	12	113	85	0	8	4	54	0	0	203	212	1
POL	19	47	10	1039	66	10	86	2435	414	1	272	3	39	2	31	4	6705	1	98	18	25	2	0	289	177	72
PRT	0	1	0	1	0	0	7	4	4	0	0	0	2	0	1	0	2	208	0	100	0	0	0	0	5	0
ROM	11	10	153	316	11	3	23	376	89	10	532	1	84	0	8	1	478	0	2969	5	5	1	6	459	59	390
ESP	2	16	0	27	3	1	154	85	66	0	3	2	38	1	7	0	31	102	1	2738	1	2	0	3	93	9
SWE	1	27	1	91	129	121	34	323	157	0	18	4	2	1	20	36	239	1	15	4	430	0	0	332	205	3
CHE	4	13	0	24	2	0	116	77	90	1	5	1	179	1	4	0	17	1	2	13	1	114	0	2	44	11
TUR	3	4	149	79	5	2	8	124	30	111	82	1	32	0	4	0	135	0	192	7	2	0	442	229	23	59
SUN	31	80	117	1104	135	341	141	2117	561	41	766	8	145	2	54	18	3775	1	1012	32	128	3	44	2669	406	299
GBR	1	54	1	46	14	2	86	168	134	0	5	51	2	1	41	2	50	1	2	18	4	0	0	19	4761	3
YUG	45	24	162	392	9	2	76	486	166	40	531	1	456	1	13	1	295	1	173	18	3	5	7	108	91	2430
Total	486	1493	3033	8972	791	1086	4410	18245	7992	608	4926	265	4998	58	758	192	14235	334	5209	3448	769	217	526	2944	8427	4270

Note: Emitters are column countries and recipients are row countries, Source: Sandnes (1993).

Table 4A. Empirical $\tilde{A}$ Sulfur Transport Matrix for 1985.

	AUT	BEL	BGR	CSK	DNK	FIN	FRA	DDR	DEU	GRC	HUN	IRL	ITA	LUX	NLD	NOR	POL	PRT	ROM	ESP	SWE	CHE	TUR	SUN	GBR	YUG
AUT	0.000	0.017	0.000	0.021	0.003	0.001	0.016	0.015	0.023	0.001	0.012	0.003	0.016	0.038	0.012	0.000	0.007	0.000	0.002	0.001	0.001	0.029	0.000	0.000	0.005	0.014
BEL	0.000	0.000	0.000	0.001	0.002	0.000	0.015	0.002	0.013	0.000	0.000	0.003	0.000	0.025	0.025	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.007	0.000
BGR	0.004	0.001	0.000	0.005	0.001	0.001	0.001	0.003	0.002	0.008	0.015	0.000	0.003	0.000	0.001	0.000	0.004	0.000	0.036	0.000	0.001	0.000	0.004	0.002	0.001	0.022
CSK	0.042	0.015	0.001	0.000	0.009	0.001	0.010	0.053	0.025	0.000	0.060	0.003	0.004	0.025	0.013	0.002	0.037	0.000	0.009	0.001	0.003	0.006	0.000	0.001	0.006	0.013
DNK	0.000	0.005	0.000	0.002	0.000	0.001	0.002	0.004	0.006	0.000	0.001	0.003	0.000	0.000	0.008	0.008	0.002	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.005	0.000
FIN	0.001	0.003	0.000	0.003	0.013	0.000	0.001	0.005	0.004	0.000	0.001	0.001	0.000	0.000	0.004	0.016	0.007	0.000	0.000	0.000	0.044	0.000	0.000	0.013	0.003	0.000
FRA	0.010	0.105	0.000	0.014	0.012	0.001	0.000	0.020	0.051	0.000	0.005	0.021	0.023	0.150	0.053	0.002	0.007	0.014	0.002	0.030	0.004	0.042	0.000	0.001	0.033	0.006
DDR	0.005	0.023	0.000	0.040	0.021	0.001	0.010	0.000	0.043	0.000	0.004	0.004	0.001	0.025	0.025	0.002	0.013	0.000	0.001	0.001	0.005	0.002	0.000	0.000	0.008	0.001
DEU	0.021	0.109	0.000	0.030	0.030	0.001	0.065	0.060	0.000	0.000	0.005	0.016	0.007	0.163	0.104	0.004	0.013	0.002	0.001	0.005	0.006	0.046	0.000	0.001	0.031	0.004
GRC	0.003	0.001	0.016	0.003	0.001	0.000	0.001	0.002	0.002	0.000	0.007	0.000	0.004	0.000	0.001	0.000	0.002	0.000	0.010	0.000	0.001	0.000	0.009	0.001	0.001	0.009
HUN	0.030	0.004	0.001	0.023	0.003	0.001	0.004	0.010	0.006	0.001	0.000	0.001	0.006	0.000	0.004	0.000	0.010	0.000	0.017	0.000	0.001	0.002	0.001	0.001	0.002	0.034
IRL	0.000	0.003	0.000	0.000	0.001	0.000	0.001	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000
ITA	0.031	0.012	0.001	0.016	0.004	0.001	0.027	0.013	0.015	0.008	0.016	0.003	0.000	0.025	0.009	0.000	0.009	0.002	0.003	0.004	0.002	0.060	0.002	0.001	0.005	0.029
LUX	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NLD	0.000	0.042	0.000	0.002	0.003	0.000	0.009	0.004	0.024	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.011	0.000
NOR	0.001	0.008	0.000	0.003	0.022	0.013	0.003	0.005	0.006	0.000	0.002	0.010	0.000	0.000	0.009	0.000	0.004	0.000	0.001	0.000	0.037	0.000	0.000	0.004	0.011	0.000
POL	0.019	0.021	0.001	0.075	0.038	0.005	0.012	0.090	0.035	0.000	0.039	0.004	0.003	0.025	0.022	0.008	0.000	0.001	0.011	0.002	0.017	0.004	0.000	0.005	0.010	0.010
PRT	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000
ROM	0.011	0.004	0.013	0.023	0.006	0.002	0.003	0.014	0.007	0.004	0.076	0.001	0.007	0.000	0.006	0.002	0.022	0.000	0.000	0.000	0.003	0.002	0.004	0.008	0.003	0.052
ESP	0.002	0.007	0.000	0.002	0.002	0.001	0.021	0.003	0.006	0.000	0.000	0.003	0.003	0.013	0.005	0.000	0.001	0.103	0.000	0.000	0.001	0.004	0.000	0.000	0.005	0.001
SWE	0.001	0.012	0.000	0.007	0.075	0.063	0.005	0.012	0.013	0.000	0.003	0.006	0.000	0.013	0.014	0.072	0.011	0.001	0.002	0.000	0.000	0.000	0.000	0.006	0.011	0.000
CHE	0.004	0.006	0.000	0.002	0.001	0.000	0.016	0.003	0.008	0.000	0.001	0.001	0.014	0.013	0.003	0.000	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.002	0.001
TUR	0.003	0.002	0.013	0.006	0.003	0.001	0.001	0.005	0.003	0.044	0.012	0.001	0.003	0.000	0.003	0.000	0.006	0.000	0.021	0.001	0.001	0.000	0.000	0.004	0.001	0.008
SUN	0.032	0.035	0.010	0.079	0.078	0.179	0.019	0.078	0.047	0.016	0.109	0.011	0.012	0.025	0.039	0.036	0.176	0.001	0.112	0.003	0.088	0.006	0.027	0.000	0.022	0.040
GBR	0.001	0.024	0.000	0.003	0.008	0.001	0.012	0.006	0.011	0.000	0.001	0.073	0.000	0.013	0.030	0.004	0.002	0.001	0.000	0.002	0.003	0.000	0.000	0.000	0.000	0.000
YUG	0.046	0.011	0.014	0.028	0.005	0.001	0.010	0.018	0.014	0.016	0.076	0.001	0.036	0.013	0.009	0.002	0.014	0.001	0.019	0.002	0.002	0.010	0.004	0.002	0.005	0.000

Note: Entries are α_{ij}s. Emitters are column countries and recipients are row countries. Source: calculated from Sandnes (1993).

Table 5A. Maximum Likelihood Estimtes of the Sulfur Emission Reduction Regressions Dropping Selected Countries. Asymptotic t-ratios in Parentheses.

Variables	Without Soviet Union	Without Turkey	Without Soviet Union and Turkey			
			(1)	(2)	(3)	(4)
SPILL	-6.401 (-28.70)	-4.241 (-21.67)	-6.498 (-29.02)	-6.441 (-28.76)	-7.456 (-37.63)	-6.679 (-30.68)
GNP	6.633 (5.71)	5.634 (4.23)	6.832 (5.93)	6.519 (5.31)	5.995 (5.57)	7.069 (6.11)
PRICESUL	-12.816 (-0.14)	167.231 (1.61)	18.76 (0.20)	49.897 (0.48)	8.635 (0.10)	32.386 (0.34)
OWNSUL	664.964 (1.53)	999.706 (1.90)	749.556 (1.73)	1082.723 (1.68)	815.41 (2.12)	574.463 (1.24)
GASTIL	-26.517 (-2.93)	-33.141 (-3.23)	-26.895 (-3.01)	-29.431 (-3.06)	-32.711 (-4.03)	-26.13 (-2.96)
TARGET	-0.638 (-4.09)	-0.845 (-4.36)	-0.709 (-4.36)	-0.729 (-4.45)	-0.516 (-3.19)	-0.724 (-4.51)
HELSINKI	123.28 (2.56)	106.512 (1.81)	110.971 (2.29)	130.365 (2.33)	154.158 (3.41)	115.004 (2.42)
FOREST				-1.326 (-0.69)		
CONIFER					-7.785 (-2.47)	
BROADL						-2.628 (-0.92)
CONSTANT	-125.232 (-1.21)	-148.103 (-1.18)	-129.217 (-1.26)	-170.389 (-1.45)	-62.642 (-0.67)	-70.654 (-0.60)
-Log Likelihood	131.033	134.84	125.525	125.288	123.098	125.121

Note: BROADL denotes the percentage of a nation's broadleaf trees with more than 25 percent defoliation, while CONIFER indicates the percentage of a nation's conifers with more than 25 percent defoliation. Source: UNEP (1993).

Table 6A. Maximum Likelihood Estimtes of the Sulfur Emission Reduction Regressions when Nonvoluntary (Target) Spillins (TSPILL) Are Included. Asymptotic t-ratios in Parentheses.

Variables	Models (1)	(2)	(3)	(4)
SPILL	-5.631	-3.337	-3.811	-3.867
	(-21.77)	(-17.81)	(-22.29)	(-22.93)
GNP	2.428	7.275	8.306	7.881
	(2.53)	(5.28)	(5.54)	(4.97)
PRICESUL	84.291	8.00	60.693	86.657
	(0.61)	(0.07)	(0.54)	(0.75)
OWNSUL	1377.304	367.319	666.839	1126.99
	(1.61)	(0.54)	(0.99)	(1.26)
GASTIL	-52.132	-17.69	-13.757	-16.942
	(-4.46)	(-1.51)	(-1.18)	(-1.38)
TSPILL	0.999	1.498	0.965	0.851
	(0.66)	(1.30)	(0.84)	(0.74)
TARGET		-0.857	-1.03	-1.011
		(-4.86)	(-4.73)	(-4.67)
HELSINKI			110.293	134.694
			(1.42)	(1.62)
FOREST				-1.740
				(-0.76)
CONSTANT	-45.97	10.838	-141.963	-199.926
	(-0.27)	(0.08)	(-0.86)	(-1.12)
-Log Likelihood	149.862	142.083	141.149	140.863

Note: TSPILL is the cumulative nonvoluntary (targetted) spillin or reduced sulfur emissions due to reductions in other sample nations.

Table 7A. Maximum Likelihood Estimates of the NO_x Emission Reduction Regressions. Asymptotic t-ratios in Parentheses.

Variables	Dependent Variable = NO85_90 (1)	(2)	(3)	(4)	(5)	(6)	Dependent Variable = NO80_90 (1)	(2)	(3)	(4)	(5)	(6)
SPILL	-12.769	-12.304	-12.95	-13.052	-12.599	-13.223	-3.81	-3.002	-3.73	-5.643	-4.955	-5.551
	(-10.34)	(-9.28)	(-11.59)	(-11.14)	(-9.55)	(-12.56)	(-3.82)	(-4.46)	(-3.85)	(-4.99)	(-6.39)	(-5.03)
GNP	-1.869	-1.968	-1.859	-1.914	-2.013	-1.904	-3.396	-3.715	-3.403	-3.354	-3.663	-3.363
	(-4.23)	(-4.43)	(-4.28)	(-4.57)	(-4.77)	(-4.62)	(-4.45)	(-5.12)	(-4.46)	(-4.71)	(-5.46)	(-4.72)
PRICENOX	0.290	0.248	0.378	0.639	0.600	0.719	0.438	0.296	0.405	1.136	1.00	1.100
	(1.32)	(1.12)	(1.55)	(2.17)	(2.05)	(2.34)	(1.16)	(0.82)	(0.95)	(2.28)	(2.15)	(2.09)
OWNNOX	777.788	1181.592	691.978	916.293	1322.737	832.609	1135.869	2407.42	1169.045	1368.279	2631.716	1405.482
	(1.02)	(1.39)	(0.91)	(1.26)	(1.63)	(1.15)	(0.86)	(1.73)	(0.88)	(1.11)	(2.04)	(1.13)
GASTIL	15.577	16.607	16.628	24.159	25.288	25.059	10.395	13.858	9.98	28.158	31.784	27.721
	(2.25)	(2.39)	(2.40)	(2.92)	(3.07)	(3.06)	(0.87)	(1.22)	(0.83)	(2.02)	(2.42)	(1.97)
POPDEN		24007.86			24090.62			75850.59			7544.86	
		(1.00)			(1.07)			(1.94)			(2.10)	
URBAN			-1.264			-1.208			0.475			0.525
			(-0.79)			(-0.80)			(0.17)			(0.20)
SOFIA				-101.314	-102.369	-100.079				-198.335	-199.579	-198.626
				(-1.67)	(-1.72)	(-1.68)				(-1.94)	(-2.10)	(-1.94)
CONSTANT	-169.038	-203.128	-112.754	-268.62	-303.891	-213.651	-151.482	-259.143	-172.449	-353.064	-461.856	-376.515
	(-1.59)	(-1.84)	(-0.89)	(-2.30)	(-2.53)	(-1.59)	(-0.83)	(-1.43)	(-0.78)	(-1.79)	(-2.42)	(-1.63)
-Log Likelihood	136.95	136.468	136.645	135.622	135.078	135.311	149.162	147.408	149.148	147.458	145.427	147.437

Note: The NO80_90 models use the 1985 values for GNP and GASTIL. The NO85_90 models use the 1988 values. NO80_90 indicates voluntary reductions in NO_x from 1980 to 1990, calculated as the difference between 1980 NO_x and 1990 emissions. NO85_90 indicates voluntary reductions in NO_x from 1985 to 1990, calculated as the difference between 1985 NO_x and 1990 emissions.